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COMMUNICATION ASPECTS IN URBAN TERRAIN

by

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December 2006

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The nature of warfare has changed dramatically during the last decade. Western armies are increasingly required to conduct complex operations in urban terrain against asymmetric threats. These opponents use cities and their inhabitants for cover and concealment. In such situations, modern equipped armies often cannot fully utilize many of their most powerful weapons. To overcome this situation, modern communication systems are being acquired and deployed to provide real-time reconnaissance; thereby, attempting to neutralize the threat through enhanced situational awareness. This research addresses the potential impacts of communication from airborne sensors on assisting a convoy in finding its way through a hostile city quarter (based on Mazar-E-Sharif, Afghanistan) in which militia forces try to interdict them via street blockades and ambushes. The implementation is done in the agent-based simulation Map Aware Non-Uniform Automata (MANA). The results show that the current MANA version is not sufficiently capable to handle routing problems in urban terrain. Specifically, the movement algorithm is "locally greedy" and not flexible enough to project into the future—as real human decision makers do. Many workarounds were developed to mitigate this limitation. The analysis shows that the number of blockades is the single most important factor in determining the convoy's success. Of the communication factors, network latency has the most impact. For the convoy to effectively use the information, it needs to get from the sensor to the convoy in 11 seconds.

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COMMUNICATION ASPECTS IN URBAN TERRAIN

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ABSTRACT

The nature of warfare has changed dramatically during the last decade. Western armies are increasingly required to conduct complex operations in urban terrain against asymmetric threats. These opponents use cities and their inhabitants for cover and concealment. In such situations, modern equipped armies often cannot fully utilize many of their most powerful weapons. To overcome this situation, modern communication systems are being acquired and deployed to provide real-time reconnaissance; thereby, attempting to neutralize the threat through enhanced situational awareness. This research addresses the potential impacts of communication from airborne sensors on assisting a convoy in finding its way through a hostile city quarter (based on Mazar-E-Sharif, Afghanistan) in which militia forces try to interdict them via street blockades and ambushes. The implementation is done in the agent-based simulation Map Aware Non-Uniform Automata (MANA). The results show that the current MANA version is not sufficiently capable to handle routing problems in urban terrain. Specifically, the movement algorithm is "locally greedy" and not flexible enough to project into the future—as real human decision makers do. Many workarounds were developed to mitigate this limitation. The analysis shows that the number of blockades is the single most important factor in determining the convoy's success. Of the communication factors, network latency has the most impact. For the convoy to effectively use the information, it needs to get from the sensor to the convoy in 11 seconds.

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LIST OF ACRONYMS AND ABBREVIATIONS

ABM	Agent-Based Model
C2	Command and Control
C3	Command, Control and Communications
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance
CCC	Command and Control Center
DES	Discrete Event Simulation
DOE	Design of Experiment
IR	Infra-Red
ISAF	International Security Assistance Force
KFOR	NATO Kosovo Forces
MANA	Map Aware Non-Uniform Automata
MHPCC	Maui High Performance Computer Center
MOE	Measure of Effectiveness
NATO	North Atlantic Treaty Organisation
NOLH	Nearly Orthogonal Latin Hypercube
UAV	Unmanned Aerial Vehicle

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EXECUTIVE SUMMARY

The nature of warfare has changed dramatically during the last decade. Western armies are increasingly required to conduct complex operations in urban terrain against asymmetric threats. These opponents use cities and their inhabitants for cover and concealment. In such situations, modern equipped armies often cannot fully utilize many of their most powerful weapons. To overcome this situation, modern communication systems are being acquired and deployed to provide real-time reconnaissance, thereby attempting to neutralize the threat through enhanced situational awareness. This research addresses the potential impacts of communication from airborne sensors on assisting a convoy in finding its way through a hostile city quarter in which militia forces try and interdict them via street blockades and ambushes.

The vignette chosen to explore the communication aspects in urban combat is inspired by the "Black Hawk Down" incident in Mogadishu, Somalia. As depicted in the movie, a convoy has to make its way through a hostile city neighborhood in which militia forces build blockades and try to ambush the convoy. Unfortunately for the convoy, in Mogadishu, the delay in getting information from their airborne reconnaissance platforms (helicopters) made the information almost useless. In our situation, the convoy is trying to navigate through terrain based on Mazar-E-Sharif, Afghanistan. The airborne sensor grid supporting the convoy consists of hovering Unmanned Aerial Vehicles (UAVs). The UAVs provide near real-time information about blockades.

The scenario is implemented as an agent-based simulation using the software package Map Aware Non-Uniform Automata (MANA), see Figure 1. However, transferring a classic network routing problem into an agent-based model is not easily done. The software's limitations make it necessary to use many workarounds. In particular, the convoy's movement decisions—which MANA limits to greedy local choices—have to be made more robust. The partial screen shot (Figure 2) shows the main ideas in our approach to making the convoy behave reasonably.

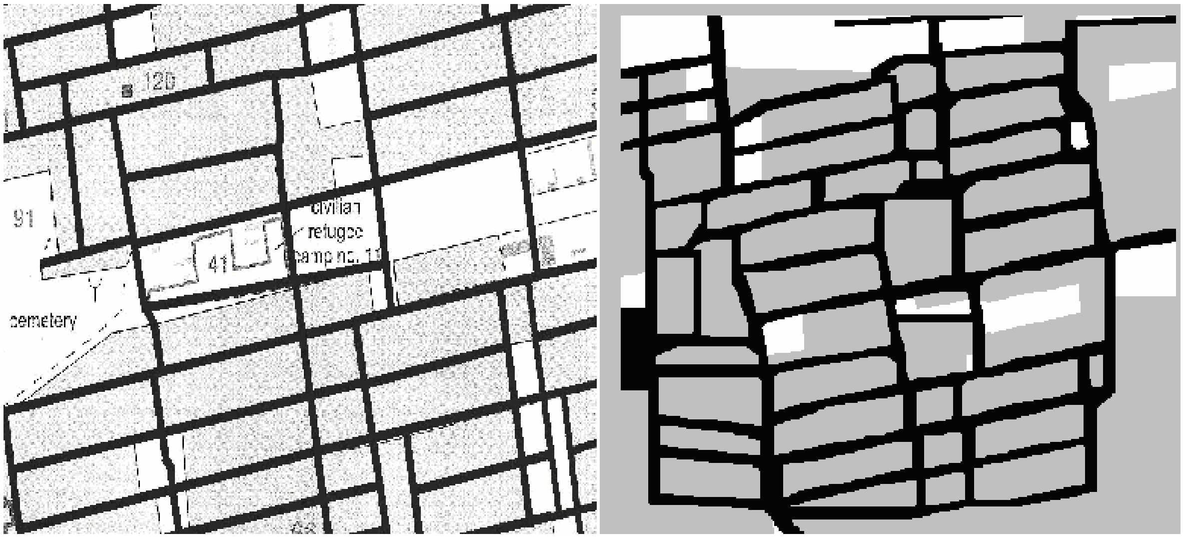

Figure 1. The original map of Mazar-E-Sharif and the MANA terrain map.

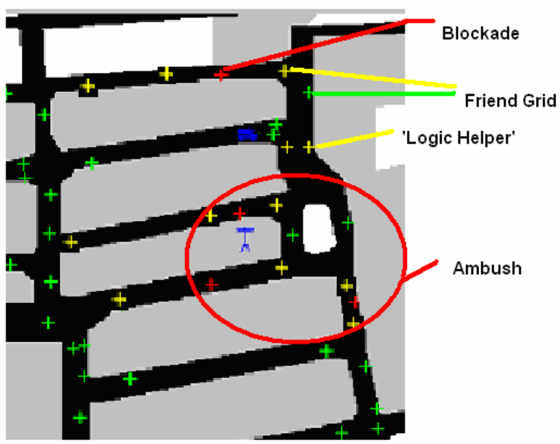

Figure 2. Helper agents used to assist the convoy in utilizing information. (Best viewed in color)

The convoy can rely on a grid of friends, comparable to the street map. These friends draw the convoy into usable streets (green) or warn it and repel it when the street is blocked (yellow). Having additional information from the sensor grid, the convoy is informed by these 'logic helpers' on which roads are clear. An important question is, how do these workarounds influence the model's quality and usability?

In order to settle the analysis on a broader base, the factors are divided into uncontrollable and controllable sets. The factors the convoy cannot control include the number and placement of blockades. The controllable factors are those associated with

its sensors and communications network. These include latency, reliability, capacity, sensor range, and update rate. Nearly Orthogonal Latin Hypercubes are used to efficiently conduct the experiments.

Two experimental sets are conducted. The first experiments help assess the model's quality by comparing the convoy's ability to successfully reach its goal under 25 blockade combinations, both with communications and without communications. That is, without communications the convoy must rely only on its own visual sensor; with communications the convoy can also take advantage of the information given to it by a grid of hovering UAVs. The measure used to quantify the effectiveness of the convoy in traveling to its objective is the number of hits the convoy suffers. The main result from the quality assessing experiment is shown in Figure 3.

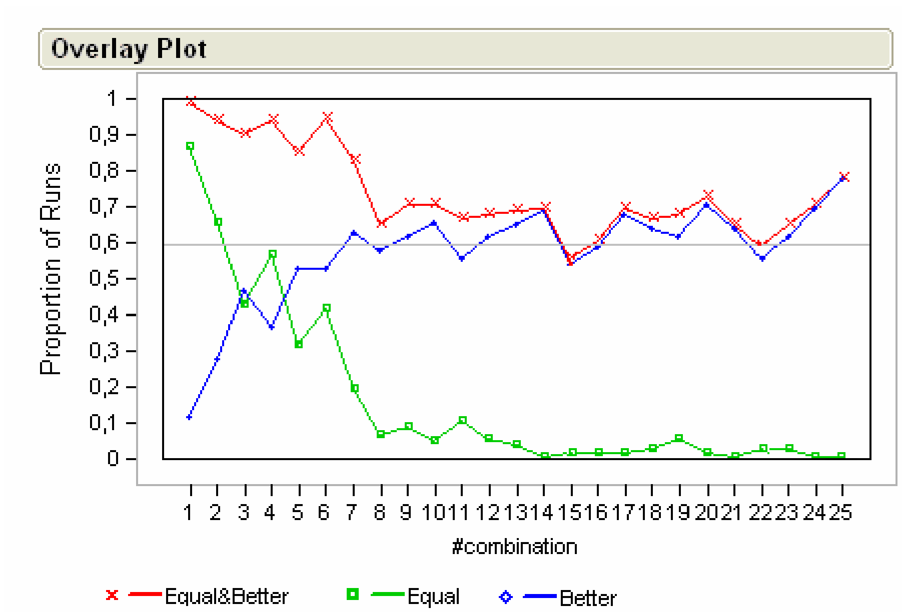

Figure 3. Proportion of times the convoy with communication does better, equal, or equal & better than the convoy without communications for 25 separate combinations of blockades. The number of blockades increases with the x-axis. (Best viewed in color)

The experiment was run to compare the convoy's behavior with and without communications. The graphical analysis reveals that for a large number of blockades the

convoy with communications does better only about 60 percent of the time—a disappointingly low number. On the other hand, the statistical analysis shows that communications has an improving impact by reducing the mean number of hits the convoy suffers for all 25 blockade configurations.

The second experiment, the main focus of this thesis, examines the communications factors. The 25 combinations of blockades are tested against 65 communication settings. This experiment contains 1625 input combinations, with 100 replications each. The analysis of the output data from these 162,500 computational experiments shows that the number of blockades has the most impact on the convoy's success. Unsurprisingly, latency within a communication network is the most important communications factor, followed by the pause (delay time) between the information updates given by the sensor grid. That is, even good information in such a situation has to be timely, or it is nearly worthless. The exclusion of other factors, such as reliability and capacity, must be taken in the context of our static scenario—i.e., there are no moving enemies. Figure 4 shows part of a partition tree on the communications factors.

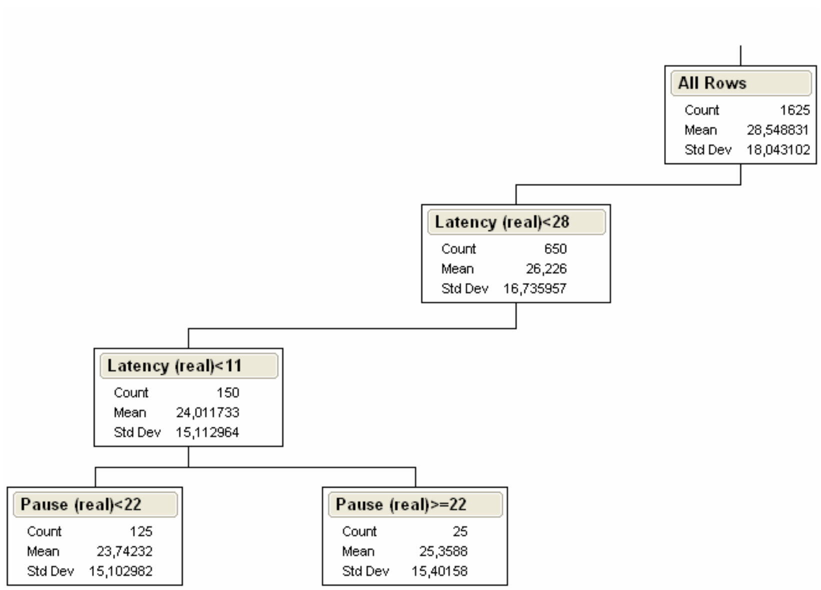

Figure 4. A portion of the regression tree with the partitions made only on communications factors. The times are in seconds. We see the importance of the hovering sensors getting information quickly to the convoy, and its effect on the mean number of hits the convoy suffers.

Other lessons learned and key takeaways from implementing this scenario in MANA include:

- The current simulation software complicates the realistic modeling of movements in urban terrain, and will continue to do so as long as a routing problem is involved. The necessity of an underlying network structure for movement decisions became obvious to the author.
- The communication links provided by the software package do not reflect the current technology standards. In order to model realistic digital communication networks, workarounds had to be used. These workarounds reduced the simplicity and the idea of agent-based models.

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I. INTRODUCTION

A. BACKGROUND

> A military unprepared for urban operations across a broad spectrum is unprepared for tomorrow. [Peters 1996]

Since the fall of the iron curtain in 1990 and the end of the Cold War, warfare has changed drastically. The old doctrines were modeled on the expectation that nearly all decisive battles would take place in open terrain. Both combatants in the Cold War—NATO and those bound by the Warsaw Pact—clearly desired to avoid combat in urban environments. Behind this intention to steer conflict away from cities was the possibility of an incalculable number of casualties in urban zones.

On the other hand, "control of cities always has been vital to military success, practically and symbolically."[1] Today, Western armies face more and more asymmetric threats in which the opponent attempts to draw the forces into an urban environment. These opponents are familiar with the area and many of the high-technology weapons of the West are largely ineffective. Furthermore, opponents use civilians in the cities as shields and restrict the engagement of weapon systems which are designed for open space combat. The current situation in Baghdad illustrates the problems that Western forces encounter in this new urban combat. American political and military leaders are clearly focused on securing the city. In fact, success in this major city will likely determine the success of the coalition forces in all of Iraq. In recent months, however, terrorist organizations have attempted to destabilize Baghdad.

The likelihood of troop engagement in cities is increasing. One factor in this new development, as mentioned before, is the opponent's strategy to use the advantage of familiar urban terrain and the cover of non-combatants in the streets. On the other hand, a modern equipped Western army lacks the opportunity to unfold its total power. As a result, this army experiences a reduced effectiveness of high-tech weapon systems and limited communications. Another aspect of increases in urban combat is the nature of

1 Ralph Peters, "Our Soldiers, Their Cities," Parameters, Spring 1996, pp. 43-50.

cities themselves. Demographic data shows that urbanization is an ongoing process. Cities act like a center of gravity, attracting people to move there. Currently, half of the world's population lives in and around cities, and a prognosis for the next century shows that about 70 percent of people will make their homes in an urbanized terrain.[2]

Even in low-intensity peacemaking and peacekeeping missions like NATO led KFOR in Kosovo, forces must be deployed in urban environments. "Operating in a potentially hostile city is every soldier's nightmare."[3] Behind each corner, out of every window, the enemy can attack the patrolling soldiers. These kinds of operations are challenging for a modern army. In a training mission conducted in Oakland, California, U.S Marines attacked an Old Navy Hospital and suffered high losses (70%) during the first hours of combat.[4] At the time, most Western armies were ill-prepared for urban operations.

In order to overcome this miserable situation, military organizations have recently made several changes in the preparation and training of their soldiers. Physical and psychological training are necessary in order that the soldier may avoid distraction caused by a totally destroyed environment and the human misery caused by war. The militaries have also improved individual equipment. Modern modular gear contains night vision goggles and a rifle with laser ranger, compass and head-ups display.

The key factor to increase survivability in urban combat, however, is and will be information sharing and collaboration. In a network-centric operation, each soldier benefits from precise information. Consequently, the situational awareness, speed of command and mission effectiveness improves dramatically.[5]

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2 Jean Kumagai, "Fighting in Streets," IEEE Spectrum, February 2001.

3 Gerald Yonas and Timothy Moy, "Emerging Technologies and Military Operations in Urban Terrain," in Michael C. Desch "Soldiers In Cities; Military Operations On Urban Terrain," 2001.

4 Jean Kumagai, "Fighting in Streets," IEEE Spectrum, February 2001.

5 Definition of Network-centric operations by MORS online, www.mors.org, October 2006.

"Real-time and detailed information is critical to the success of ground combat forces."[6] Over-the-hill-reconnaissance done by a networked, unmanned aerial sensor system provides the commanding officer pertinent information. Thus, troops can cover more area and gain situational awareness to aid them in the hostile environment.

Successful reconnaissance systems will therefore meet the following requirements:[7]

- Detect, identify, and track enemy targets,
- Be equipped with robust, secure and stealthy sensor arrays and
- Contain jam resistant links for sensor fusion and command and control.

Furthermore, in order to reach the commanding officer or fighting soldier in real-time, data processing from the sensor to command and control must be automated. Challenges such as the amount of collected data and making comparisons with databases to recognize and classify an enemy correctly are expected to be solvable with technology. By automating these data intensive procedures, human intervention would normally be excluded from this process and thus would reduce latency.

B. GERMANY'S C4ISR APPROACH

At this time, the German Armed Forces does not possess fully networked capabilities. They have recognized, however, that C4ISR (command, control, communications, computers, intelligence, surveillance and reconnaissance) is the heart of modern warfare.[8]

Efforts to achieve a network-centric military are often slowed by budget concerns. The lion's share of the German military procurement budget is spent on a few major acquisitions (e.g., Eurofighter, air-transporter AIRBUS 400M, Tiger and NH-helicopters). The German military must purchase all of these investments in fulfillment of long-binding contracts with German and European companies.

6 Gene Klager, "Networked Sensors for the Combat Forces," in "Unmanned/Unattended Sensors and Sensor Networks," Edward M. Carapezza (Editor), November 2004, pp. 204-214.

7 Jay Nemeroff, Luis Garcia, Dan Hampel, Stef DiPierro, "Application of Sensor Network Communications," IEEE 2001.

8 Gordon Adams, Guy ben-Ari, John Logsdon, Ray Williamson, "Bridging the Gap," October 2004.

Another obstacle to progress in networking capability is the lack of interoperability among existing C3 equipment. For example, HEROS (Army command and control system for digitally-supported command operations in staffs) is introduced to corps, divisions and brigades. This system has no interface to the lower echelon system FAUST (command and control provision) for regiments and battalions.

The FAUST system is mounted on most of the vehicles and tanks operating in Afghanistan and Kosovo and delivers a variety of support for the forces. Its updated map mirrors the friendly forces' positions and the reconnaissance results about the enemy that have been entered manually. Other tools are also helpful, such as emergency call, free text messages and automated updates and reports concerning the position of the vehicle.

The German Army has one successful UAV at its disposal. The drone CL-289 is able to take black/white or infrared pictures and deliver real-time video data. These results must be analyzed by operators and entered into the C3 software packages. Other UAV programs have been abandoned during recent years due to budget limitations.

The German Army will attempt to overcome their technological handicap by achieving interoperability between the C3 systems and with other branches and allies. The automated data entries are absolutely necessary to gain a real-time information flow in an ongoing operation.

New UAV programs have been launched to improve over-the-hill reconnaissance capabilities with the forces. One such program has resulted in the FANCOPTER (shown in Figure 5), developed by EMT. The FANCOPTER is a small hovering UAV specially designed for missions in urban terrain or indoors. With a rotor diameter of half a meter, the UAV stabilizes in a position by using acceleration sensors which measure the wind speed. The FANCOPTER may be equipped with different camera types, including digital, video, or IR camera. At this stage of development, its radius of action is about 500 meters, and the maximum mission length is about 20 minutes.

Figure 5. FANCOPTER developed by EMT Penzberg. (From: www.emt-penzberg.de (August 2006)).

A fully functional C4ISR system is essential to the German Army. Since the reunification in October 1990, the German Armed Forces have begun to support United Nations missions. As a NATO member, Germany also took part in the Kosovo invasion after the air strikes in 1999.

For the last four years, Germany has contributed a large contingent to the stabilization forces in Afghanistan (ISAF). The latest news shows that the war on terrorism has not yet been won in this region. The threat to German soldiers in this mission abroad is constantly increasing.

With the transfer of the main contingent from Kabul to Mazar-E-Sharif completed, Germany has taken over the responsibility for the Northern Province. A map of Mazar-E-Sharif is used for the vignette presented later in this thesis.

The vignette in this thesis is modeled in MANA. This agent-based simulation is well-accepted in the simulation community. The scenario is also implemented in IT-SimBw. Besides the development and procurement of modern communication technology, "The German Armed Forces Federal Office for Information Management and Information Technology," in cooperation with Fraunhoffer Institute, started to build IT-SimBw as a new agent-based simulation tool that will examine communication aspects of combat. The first demonstrations of this new software package were done during the Project Albert workshops in Honolulu in February 2006 and Boppard, Germany in June 2006. Modeling insights experienced during this research have proved helpful to the developers of IT-SimBw. Similarly, some limitations of the widely used

“simulation software MANA have become apparent during the course of research conducted for this thesis. It is not within the scope of this thesis, however, to make a comparison between these simulation packages.

C. SCOPE

The thesis research operates on the basic assumption that the employed forces have a modern C4ISR system available for a specific mission. The listed questions of interest are addressed to explore the communication aspects of fighting in urban terrain:

- What are the impacts of various factors (latency, reliability, data updating frequency, capacity and sensor ranges) for fully networked forces engaged in a convoy mission in an urban environment?
- What are the requirements for agent-based simulation software to be effectively used to examine communications in urban terrain?

D. FLOW OF THESIS

This brief introduction is followed by a discussion of the simulation used, scenario overview, and measures of effectiveness (MOEs). The next section provides a detailed discussion of the design of the experiment which is applied to gain insights from the model. All of the parameter settings for the data farming are explained and justified. The subsequent section contains a statistical and analytical evaluation of the collected data using regression techniques and data mining tools (e.g., regression trees) in order to extract profitable insights. Finally, the findings are summarized and recommendations are given on further studies that will broaden our understanding of aspects of communication in combat situations.

II. MODEL DEVELOPMENT

This chapter deals with the model development. After explaining the scenario background and deriving the vignette, the simulation software MANA is briefly examined, including the software's limitations and the associated consequences for the model. The next section introduces the model terrain and time with their relation to real world measures. This is followed by an outline of the agents and their main behaviors. The scenario script visualizes the sequence of events during a run. The final section discusses the measures of effectiveness for the model.

A. "BLACK HAWK DOWN" SCENARIO

As discussed in the introduction to this thesis, the likelihood of combat in urban terrain is increasing. Initial thinking about successful support for ground forces during city missions began after the first unsuccessful combat in the post Cold-war era.

Filmed in the movie 'Black Hawk Down,' a failed raid on a gang leader stronghold was conducted by US forces on October 3, 1993 in Mogadishu. US Rangers were attempting to capture two high-ranking lieutenants serving Farrah Aidid, the most dangerous warlord in Somalia. The troops, sent in by helicopter, were to be picked up by a convoy and brought back to the base. The two targets were arrested successfully. However, the Somali militia reacted quickly to the attacking US soldiers and gathered behind the cover of weapons in the streets. The militia then built blockades with burning tires and cars. For the US forces, this was a new, unexpected development in comparison to previous raids.

During the campaign, two Black Hawk helicopters were shot down and the pilots were surrounded by militia and a crowd of aggressive civilians. The convoy was ordered to retrieve all soldiers from the first crash site. The situation became confused, however, because the command cell in a hovering helicopter above the city could not lead the convoy through the streets in avoidance of blockades and hostile fire. The convoy ignored the last order and focused instead on finding a route back to the base.

Thousands of Somalis took to the streets and fought against the outnumbered US Rangers who were left in the city. The US military launched a rescue campaign involving Pakistani tanks and APCs. The rescuers liberated all of the soldiers—whether dead or alive—although one pilot was held as hostage by Farrah Aidid and released after several weeks in Somali captivity. On this day, 18 American soldiers died and 73 were injured.

The vignette examined in this thesis research is only one part of the 'Black Hawk Down' scenario and is translated into a current German background. Several aspects of this scenario, which is commonly used for peace-enforcement situations, were examined in previous studies. In order to find insights about communication aspects in urban environments, this study focuses on the convoy's attempt to make its way back to base. Convoy missions are an everyday business for German troops in Afghanistan.

1. Vignette Description

The vignette is translated to a newer world. German ground forces in Mazar-E-Sharif, Afghanistan attack a gang leader stronghold and arrest the suspects. The forces are picked up by the convoy, which then must make its way through the street channels and back into the secure area where the base is located. The forces are equipped with FAUST, which has automated data updates from a sensor grid consisting of five hovering UAVs (e.g., FANCOPTER).

The well-prepared militia forces react quickly to the attack and build up blockades with different time delays to slow the convoy's movement and lead it into an ambush. These blockades appear in three waves with random compositions.

B. SIMULATION SOFTWARE AND ITS LIMITATIONS

1. MANA

The software package used for implementation is MANA Version 3.2.1. Map-Aware-Non-Uniform Automata (MANA) was developed by the New Zealand's Defense Technology Agency. In the user's manual,[9] the developers state that they developed the

9 MANA Version 3.0 Users Manual, D. Galligan, M. Anderson, M. Lauren, July 2004.

new software because their existing agent-based simulation produced outputs which differed radically from combat model's results like CAEn and Janus. The intention was not to improve a cellular automaton model, but to create a new model with new features.

An agent-based combat model (ABM) contains entities that are controlled by decision-making algorithms.[10] The agents react and interact with their surroundings (e.g., terrain, friends and enemies). MANA incorporates several new elements. For instance, the squad possesses two common situational awareness maps. These 'memory maps'[11] store the organic information[12] and inorganic information gained by communications. The agent can react differently to the kind of information it receives. The agent can also change its personality by an event-driven trigger state change. Agent-based models are usually time-stepped models, but as a part of the interactions with their surroundings, MANA agents can change their trigger states and behaviors. The duration in a state is variable.

Agent-based models are intended to provide a straightforward way to create a scenario in order to examine a special situation. In comparison to a highly-detailed combat model, the run-time is relatively short. Therefore, multiple runs over a range of input values are feasible. An efficient design of experiment combined with statistical analysis provides numerous insights and sometimes surprising results. Due to the agent's simple set of rules, however, it is possible that realization of 'correct' behavior may be more difficult to achieve.

2. Limitations and Workarounds

The developers of MANA strongly emphasize that the simulation software is not free of limitations. Two major limitations have become obvious: the greedy movement algorithm and the implementation of the communication features. These problems and their respective solutions are discussed in this section. MANA offers a number of

10 MANA Version 3.0 Users Manual, D. Galligan, M. Anderson, M. Lauren, July 2004.

11 MANA Version 3.0 Users Manual, D. Galligan, M. Anderson, M. Lauren, July 2004.

12 Contacts detected by the agents themselves or by another squad member are stored as organic information on the organic situational awareness map. On the other hand, contact data that the agents receive by a communication link is considered inorganic information, and is stored on the inorganic situational awareness map.

possibilities to circumvent the limitations by creative modeling. Varying parameters and the use of different trigger states can often help to overcome the software's weaknesses.

a. The Greedy Movement Algorithm

As mentioned in the previous section, the MANA movement algorithm operates on the agent's desires and the terrain. In order to calculate the penalty function, the software takes into account only the pixels surrounding the agent. The penalty is updated every time step. Projections into further steps are not possible in the software version used for this thesis. The agent makes its decision locally according to its desires. This differs substantially from human decision making. In a real-life situation, the convoy leader gathers all available information and processes it. His time horizon is wider, and he bases his decision on the given situational awareness and projections into the future.

In order to achieve similar agent behavior, two kinds of supporter agents have been created. The missing knowledge about the map is replaced by a grid of friend agents that send their positions constantly and reliably and act as a warning system when a street is blocked or there is no continuous route after using a street. The logic for closing streets is accomplished by 'logic helpers,' which use reaction chains in special situations. For example, when the 'logic helpers' at a four-way crossroad notice that three of the streets are blocked, then they will block the fourth street. Thus, these agents help the convoy avoid an ambush.

b. The Communication Features

The communication links implemented in MANA do not mirror the reality of current communication in combat. The data transmission between two squads is a continuous flow of information. The sender transmits its organic situational awareness map every time step. A message containing the enemy type and its location eventually reaches the recipient with high probability even if the reliability for the communication link is low. The high number of trials makes this possible.

It is difficult to interpret the capacity and reliability of the communication factors in MANA because of the fact that, in reality, messages are sent in packages. In other words, the package may or may not reach the other squad. In MANA, each contact

is put in a single message and sent with the pre-set reliability level. A partial transfer is possible and can produce absurd situations. This means that the convoy can have knowledge about an ambush without seeing all associated blockades. Unfortunately, there is no perfect solution to this problem, a drawback which will be addressed in the results discussion of Chapter IV.

3. Aggregation

Aggregation is used to reduce the complexity of the model. Agent-based models by themselves are based on simplicity. Therefore, the convoy is modeled on the movements of only one vehicle. The intra-convoy behavior (movement in line and intra-convoy communications) is outside the focus of this research and is excluded.

The same approach and argumentation is used for the blockades. As a military rule, blockades are observed, and the blockade is merged with the militiamen. That is, the blockade itself is armed.

In modern communication architectures, the sensors are linked to a Command & Control Center (CCC) that distributes the processed data back to the deployed forces. Because MANA does not allow the user to disconnect or connect a communication link by changing the trigger state, it is nearly impossible to explicitly model the CCC. However, the necessity of modeling such an element is questionable. The physical parameters like latency, reliability and duration between updating can be viewed as network parameters. The latencies in the sequential network add up, while the resulting reliability is the product of the reliabilities along the path. The updating between sensors and the CCC on one side and the CCC and the ground forces should be synchronized. Therefore, the duration between updates is a measure for the update frequency of the total network.

C. TERRAIN AND TIME

The German Army has forces deployed in the Northern Province of Afghanistan. The German Headquarters is located in Mazar-E-Sharif. For the purpose of this scenario, one square kilometer out of the Army city map was scanned. Microsoft Paint was used to draw the contours and color the map.

In the scenario, only three terrain colors are used: black (streets), grey (buildings) and white (open terrain). The movement parameters are adjusted to these colors.

The scenario terrain is not a 100 percent copy of the map. In order to gain more realistic convoy behavior, the streets have uneven width and the corners are softened. The amount of open terrain is reduced to avoid unwanted interactions. The areas around the cemetery and refugee camp are totally remodeled. The differences can be observed in Figure 6, which shows the scanned map and its 'translation' for the scenario.

Figure 6. The original map of Mazar-E-Sharif and the MANA terrain map.

The resolution employed in MANA is 1000x1000 pixels. To ensure an easy calculation, one pixel represents one meter in the real map measure.

The scale for one time step is designed as follows. In a peaceful environment, the convoy's route stretches about 1.5 km long; it takes about 1500 time steps to reach the final destination. Operating on the assumption that a convoy runs through a town with an average speed of 30 km/h, 1500 time steps in the scenario are equal to 3 minutes (180 seconds). One time step is thus about 0.12 seconds.

D. AGENTS ON THE BATTLEFIELD

This subsection describes the main characteristics of agents within the simulation. Furthermore, the section emphasizes the role of workarounds.

1. Map Grid

As mentioned in the previous section, the convoy in the simulation does not have a map. It reacts only to the local terrain and the desires it possesses according to its pre-defined personality. Therefore, friend agents have been created to support the convoy in its course through the streets of the city. As dictated by the real street network, the agents are subdivided into three groups whose number depends on the length of the street for which they are responsible. They are located at the beginning and end of various streets. Depending on the street length, an agent has a sensor range of 30, 60 or 140 meters to guarantee that the agent can detect something only in its street. By default, the map grid is completely concealed in order to avoid interactions. The map grid has a 100 percent reliable and continuous communication link to the convoy. The locations of all squad members are transmitted. This creates a kind of street network on the convoy's inorganic map. The high reliability appears as the digital map on a monitor mounted in front of the convoy leader. The behavior of each agent on the digital map is characterized by three functions. Each case is shown in Figure 7.

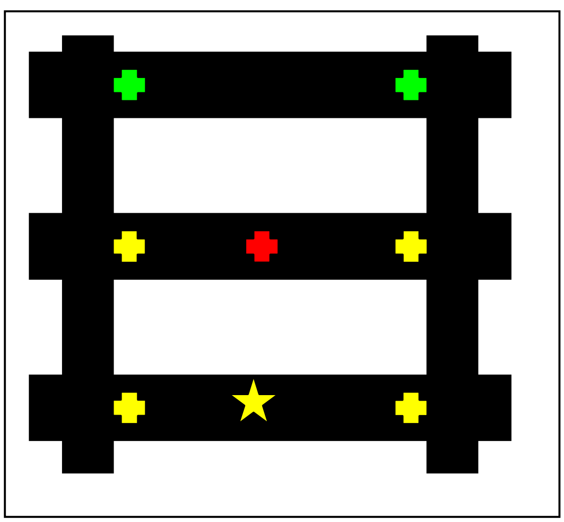

Figure 7. The three possible states of a map grid agent. (Best viewed in color)

- If the street is free and usable for the convoy, these agents have the same allegiance as the convoy.
- If an agent detects a blockade red Cross in its street (threat level 2), it changes the allegiance and becomes an unconcealed enemy with threat level 1. This action is identical to leaving the squad; therefore, the agent's location is no longer transmitted to the convoy.
- If an agent detects a 'logic helper' in its street (yellow star enemy threat 3), it becomes an unconcealed neutral. As in the case of a red Cross, it leaves the squad and vanishes from the inorganic map of the convoy.

The convoy's reaction to the different states of map grid agents will be described in the section on convoy behavior.

2. Blockades

The scenario consists of three blockade squads (A, B and C) consisting of varying numbers of agents (12, 15 and 18). Blockade A becomes active when the convoy starts its movement. Blockade B is hidden for 215 time steps (26 seconds) and appears with its resulting 'logic helpers.' Finally, the last wave of blocked streets, blockade C, is activated after another 545 time steps (65 sec).

The scenario setting is organized in the first phase of the simulation. The blockade-agent goes through a sequence of states, as illustrated in Figure 8. During the RUN START state, the agent remains totally concealed; after a fixed duration, the agent transitions into SPARE 1 STATE, where it becomes visible and vulnerable to attacks by super-agents. If the agent is killed, it disappears; otherwise, it steps into SPARE 2 STATE. The now invulnerable blockade-agent rests in the state for a fixed amount of time in order to set up 'logic helper' correctly. When this preparation is complete, the agent transitions into SPARE 3 STATE, where it hibernates, totally concealed. The blockade remains fixed up to the point in the scenario timeline when its blockade wave is activated. The active phase starts with the DEFAULT STATE. The durations may vary depending on the blockade wave and the number of necessary logical chains.

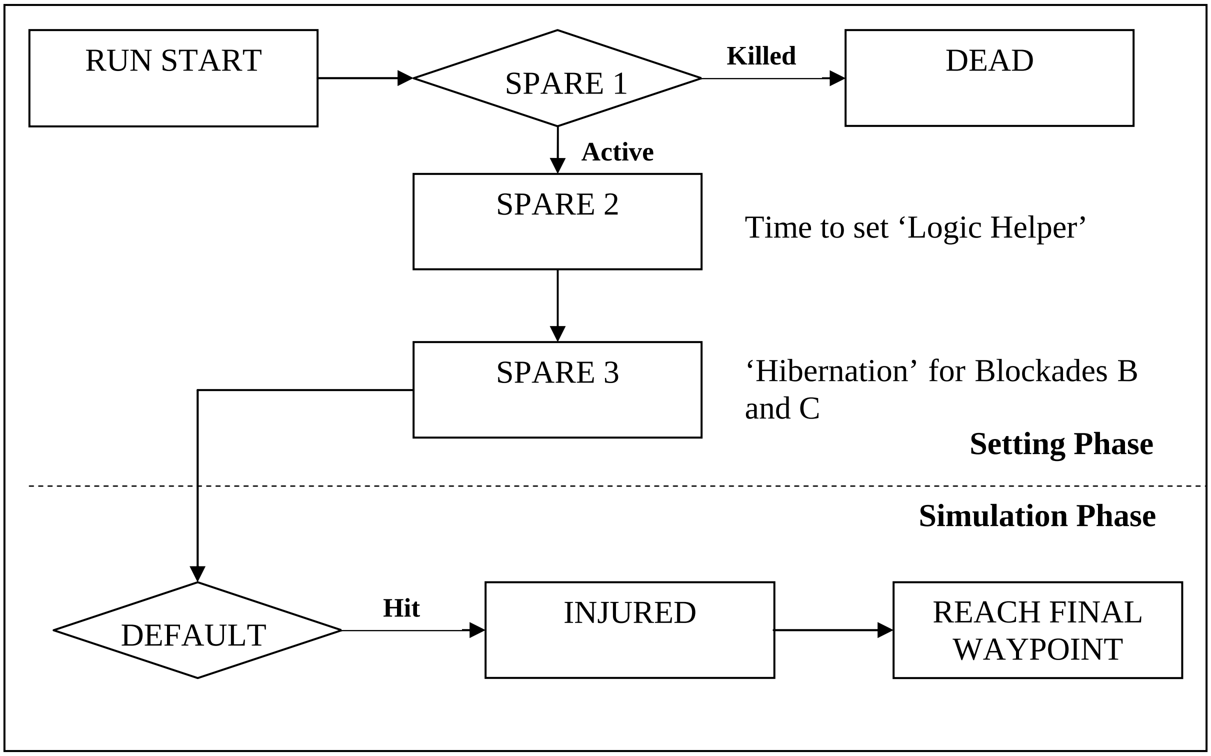

Figure 8. Sequence of states for a blockade-agent.

As mentioned, the militia guarding the blockade is aggregated with the blockade. In this scenario, the militia consists of five guards armed with 100 rounds of ammunition each. In the DEFAULT STATE, the blockade possesses a weapon available with 500 rounds. The probability of hitting the target with a single shot depends on the distance to the target (see Table 1). There are three levels implemented. The data entries are based on military norms. The probability entries represent one shot per time step.

Distance to target [meters]	**Probability [percent]**
50	30
100	20
200	10

Table 1. Probability of a successful shot depending on the distance to the target.

The convoy can open the blockade with its weapon. In this case, the blockade suffers an injury and changes its threat and class level within the state transitions. The convoy no longer recognizes the blockade as an attackable enemy. No weapon is available to the blockade in the states INJURED and REACH FINAL WAYPOINT. In the real world, all blockade militia have been neutralized and the convoy has run through the burning tires.

The numbers of injured blockades acts as a measure of effectiveness (MOE) for the examination of the impact of communication. It signifies that the convoy has been forced to fight through rather than maneuver around a blockade.

3. 'Logic Helper'

In order to support the convoy's decision concerning which route to take through the city, the simulation creates 'logic helpers.' These helpers recognize an ambush and close the street leading into the trap. They give the convoy a kind of human logic thinking.

The helper-agents appear in teams of two, each of which has contrary allegiance. A short example serves to illustrate how the helpers act and react (Figure 9).

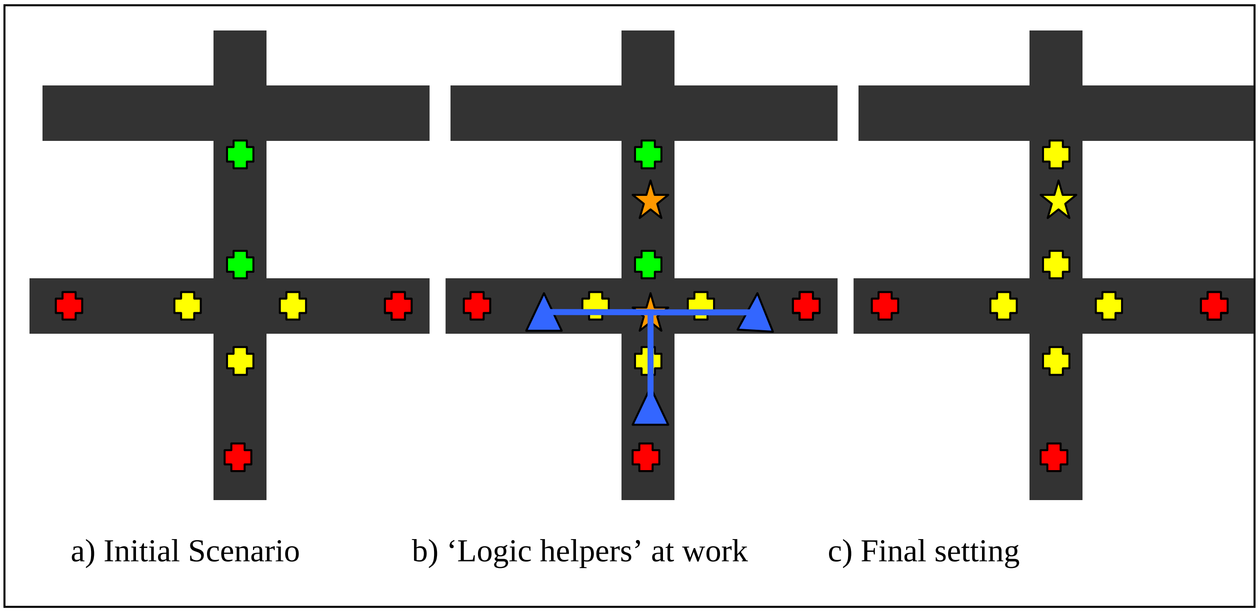

Figure 9. Demonstration of the 'logic helper'-agent. (Best viewed in color)

The initial situation at the crossroad (a) develops as follows. The enemy has set up an ambush at a four-way-crossroad by blocking three streets. The blockades (red crosses)—enemy threat 2—have been detected by the map-agents, which change their behavior (yellow crosses). The convoy thus recognizes one street as usable (green crosses).

The 'logic helpers' consist of two squads: the blue triangles (b) and the orange 5-point-stars. The triangle-agent notices the blockades and shifts into a trigger state in which it has a perfect weapon with one round of ammunition. Otherwise, the agent leaves the scenario. The agent opens fire only on the nearest 5-point-star-agent, which appears in the simulation simultaneously with the triangle-agents. After firing, the triangle-agent disappears.

The 5-point-star-agent can suffer a specified number of hits, depending on the street constellation. In this case (b), three hits are necessary to kill the 5-point-star-agent. The death of the squad member results in a trigger state transition (SQUAD DEATH), where the surviving 5-point-star-agent becomes an enemy threat level 3. Map-agents recognize this change and become neutrals, thereby closing the previously unblocked street (c).

From the convoy's perspective, the final setting develops as follows. The map grid friend detects the 'logic helper' in its street and becomes a neutral. The convoy will get the information about the neutral via communication link. The convoy will then know the blockade constellation and the neutral's location. The neutral does not allow the convoy to enter the street leading into the ambush.

There are a variety of 'logic helpers' which use principles similar to those outlined above. The trigger state transition of triangle-agents can also be activated by a neutral or an enemy threat 3. On the other hand, the surviving 5-point-star-agents can mutate to neutrals and close the road directly. When the final setting is complete, the helpers, like the blockades B and C, hibernate until the associated blockade wave enters the scenario.

4. Sensor Grid

MANA structures communication as a continuous flow of information along the link. At each time step the organic and/or inorganic information is transmitted to the recipient. In a modern digital data network, information is packed, sent and frequently updated. A sensor enters an 'offline' mode regarding the communication link between updates of the information.

In order to achieve this behavior, MANA implements a perfect cookie-cutter sensor that alternates between two states during the main phase of the simulation. The use of a sensor that would frequently misclassify contacts would lead to chaotic situations within the scenario. The logical chaining relies on accurate information about detected agents, and therefore requires the perfect sensor. Due to the fact that MANA does not have a 3-dimensional picture, however, the hovering UAV is placed on the ground and can scan through walls. In actual combat situations, the UAV altitude would be chosen in order to have maximum view of the ground.

The sensor-agent's behavior is visualized as a flow chart in Figure 10. After the setting phase (RUN START STATE), the sensor-agent scans the environment within its sensor range and enters the information onto its organic map, where it remains for only one time step. This data is sent to the convoy's inorganic map. There is only one chance to put the data in the communication queue. In the next step (SPARE 2 STATE), the sensor grid goes blind by setting its sensor range to zero. The agent stays in this mode for a fixed duration before it automatically falls back into SPARE 1 STATE and receives the sensor capability.

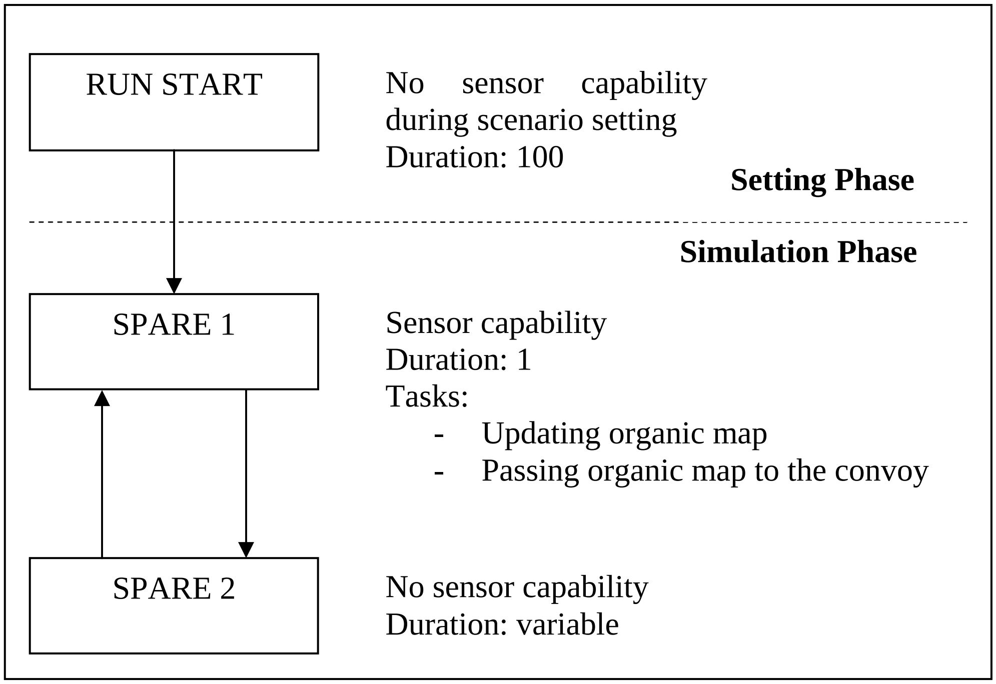

Figure 10. The sensor behavior.

The sensor grid is built by five sensors possessing a direct link to the convoy. The communication parameters—latency, reliability, capacity, the sensor range and the pause between updates (duration in SPARE 2)—vary as factors in the simulation. The sensors remain in fixed positions during the simulation. Normally, a sensor grid is a self-maintaining system designed to optimize coverage of the area.

5. Super-Agents

The scenario contains three squads of super-agents associated with one blockade wave. These squads guarantee a random setting of the blockades within the wave. Different intensity levels are created by varying the number of super-agents per squad. The number of blockades in a specific wave thus becomes a controllable enemy factor.

A super-agent has a perfect cookie-cutter sensor and a perfect weapon with one round of ammunition. The agent reacts to the appearance of its associated blockade wave (synchronized by RUN START STATE), chooses its target randomly and kills it. MANA excludes the possibility that squad members may shoot at the same target simultaneously. After firing, the agent falls back into AMMO OUT STATE, after which it disappears from the scenario map.

6. Convoy

The convoy is simulated by one agent. The aggregation, as mentioned before, reduces the complexity in order to model the correct convoy behavior of several vehicles and their intra-squad communications. The convoy is located at its starting point during the setting phase of the scenario but does not move. Fuel status is used as a surrogate for urgency in returning to base, since actual fuel requirements are not used in the model. The convoy transitions automatically into the REFUEL BY FRIEND state. After 2200 time steps (real world: about 4½ min) it jumps into the FUEL OUT state. This behavior change results in a desire to reach the base as quickly as possible. Figure 11 demonstrates this organic behavior— information gathered by the convoy's visual sensor—by showing the differences between the two trigger states.

Figure 11. The convoy's organic setting in REFUEL BY FRIEND (left) and FUEL OUT (right).

In the beginning of the simulation phase, the convoy attempts to avoid the blockades that it has visually detected. The map-agents (Enemy Threat 1) strongly repel the convoy when they are in close range. The blockades themselves also have a deterrent character within the convoy's sensor range (400 meters). In this scenario, the agent considers only one waypoint to be its final destination—the base. The NEXT WAYPOINT draws the agent.

When the convoy shifts into FUEL OUT, the final destination becomes a stronger focal point while the blocked streets deterrence parameters are reduced. The convoy will now run through the blockades in order to reach the secure area. In both states, the convoy has a ‘short-distance-weapon’ to open a blockade. The agent can use the weapon in a radius of 25 meters around a blockade, and will hit the barrier with certainty.

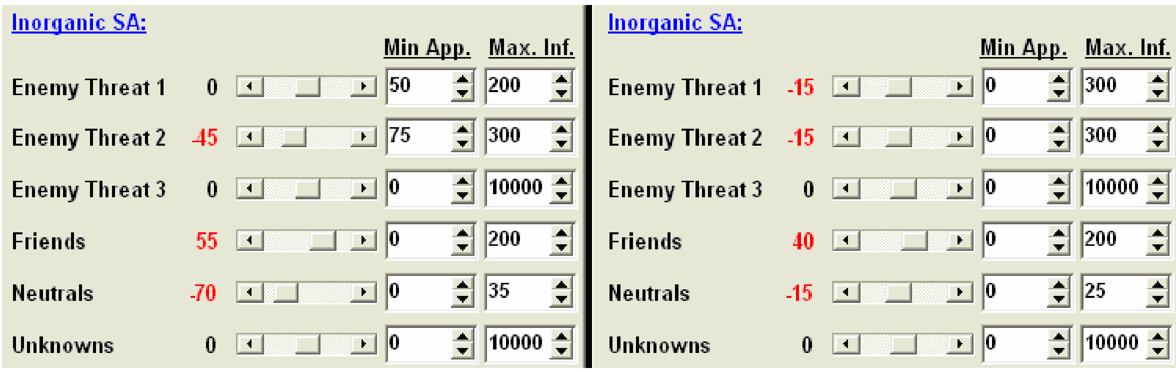

Figure 12. The convoy’s inorganic settings parameters in the REFUEL BY FRIEND (left) and FUEL OUT (right).

Similar to the organic parameters, the inorganic parameters change during the transition. At the start, the convoy avoids streets blocked by ‘logic helpers’ because of the repellant nature of neutrals. In addition, the convoy uses its inorganic information to stay away from blockades. The map agents draw the convoy toward usable streets. In the FUEL OUT state, the levels for blocked streets are set low (-15) and the friend attraction is reduced in comparison to the previous trigger state to support the organic desire to reach the final destination.

E. SCENARIO SCRIPT

The script of the scenario is visualized in the following figure. The figure demonstrates the subdivision—setting and simulation phase—and the associated time steps between the events. One purpose of separating the setting and simulation phase lies

in the comparability. Using the same seed[13], setting identical levels for the blockades and varying only the communication factors result in the same enemy set up. This makes a pair-wise comparison of runs possible.

The events are summarized for the different agents in Figure 13.

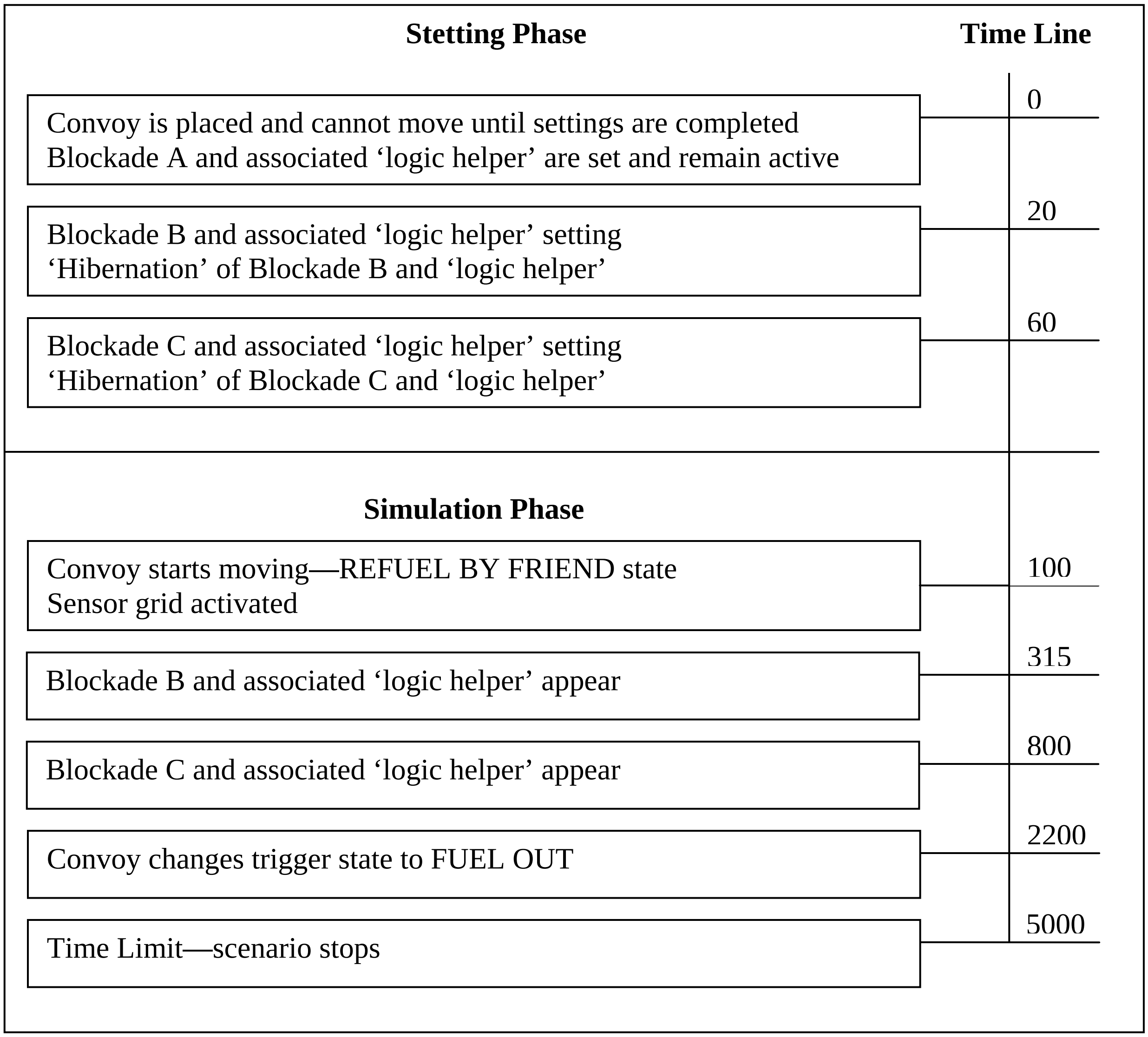

Figure 13. The scenario script.

13 From the MANA Manual p. 14: "Seed: This number is used to generate all the random numbers used in a run (start position, hit probabilities etc.)." It was observed that small changes in the terrain file and in the numbers of agents placed on the battlefield lead to different blockade settings, even using the same seed.

F. MEASURE OF EFFECTIVENESS

MANA generates an EXCEL file that includes several fields, such as 'Reach Final Waypoint,' run time, number of casualties in each squad and number of injured members within a squad. This file contains one row per run. The software package also delivers one output file per run which stores all agents' end state data. This file shows the state in which the agent ended its final location and the number of hits.

The MOEs for the simulation are derived and extracted from this available data collection. These MOEs are directly related to the research focus and will be defined precisely. They are mutually exclusive in order to avoid overlapping.

- Communications influence the convoy's route through the street channels. Therefore, the mission length is deduced by subtracting the setting phase from the run time. The linear transformation is done in the data post-processing.
- The precision of the information transmitted via the communication link leads the convoy to pursue different paths through the city, resulting in different numbers of broken blockades. This number is also a MOE, and is calculated by adding the number of injured members within the blockade squads.
- Communications affect the number of hits the convoy suffers. A Ruby[14] script is used to read the data out of the agent end state files. The routine opens the file by the predefined filename and reads out the identification (run and excursion), the needed information final location and the number of hits.
- In the case that the convoy does not reach its final destination, its last position in the scenario leads to conclusions about the cause of its failure.

An explanation of which MOEs are the most reliable indicators is made in Chapter IV, after the analysis of the collected data.

14 Ruby is an open source programming language which provides excellent scripting and data manipulation capabilities. Available at http://www.ruby-lang.org/en.

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III. DESIGN OF EXPERIMENT

Combined with an efficient Design of Experiment (DOE), the MANA simulation tool provides a good seed for the data farming and promises a successful harvest. This chapter focuses on the DOE used to verify the model and gain insights about communication aspects in urban terrain. First, the Nearly Orthogonal Latin Hypercube (NOLH), the main DOE technique used in this thesis, is introduced together with its strengths and weaknesses. Factors for the scenario are divided into two groups, controllable and uncontrollable. The design used for each group is explained. In the last step, the designs for assessing the model quality and examining communication aspects are derived.

A. THEORY OF NEARLY ORTHOGONAL LATIN HYPERCUBES

Insight occurs most efficiently in experiments that vary several factors simultaneously. One possibility is a full factorial design. Such a design contains all combinations between all factor levels. Despite the ready availability of computing power today, the number of runs increases exponentially upon the addition of factors and levels. In order to examine 4 factors with 10 levels each, 10,000 (= 10^4) design points would be necessary. This must further be multiplied by the number of replications for each design point. The total number of runs quickly reaches millions or more when several factors are explored. These kinds of gridded designs are thus useful only for a small number of factors and levels.

Lieutenant Colonel Thomas Cioppa, an NPS PhD graduate, researched in the area of experimental design and found a 'smart' solution to reduce the number of design points while still covering the factor space efficiently. In his dissertation,[15] he examined the use of Nearly Orthogonal Latin Hypercubes. The main characteristics for a NOLH design and the resulting consequences are briefly summarized:

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15 Lt.Col Tomas M. Cioppa, "Efficient Nearly Orthogonal and Space-Filling Experimental Designs for High-Dimensional Complex Models," PhD dissertation, Operations Research department, Naval Postgraduate School, Monterey, 2002.

- The input factors are nearly uncorrelated. Therefore, the design has properties that accommodate statistical analysis. Specifically, multicollinearity is not a concern when using linear regression.
- The space-filling properties of the design points sample across the input space.
- The reduction of design points when compared to a full factorial design, does not substantially decrease the capability to analyze many effects and interactions.

A NOLH design opens the opportunity to simultaneously examine a large number of input factors. Although this thesis does not focus on the theory and mathematical background for NOLHs, it is a useful tool to explore a variety of input factors within a reasonably sized experiment.

A small example, see Figure 14, demonstrates the differences between a 2^k-factorial design and NOLH-design involving four continuous factors with a range of 1 to 10. A low-high (2 level) design is compared to a NOLH design[16] with 17 design points. The number of design points are nearly identical with 16 (2^4) and 17, but the spread across the 4-dimensional input space is different, as evident in the pair-wise scatterplots.

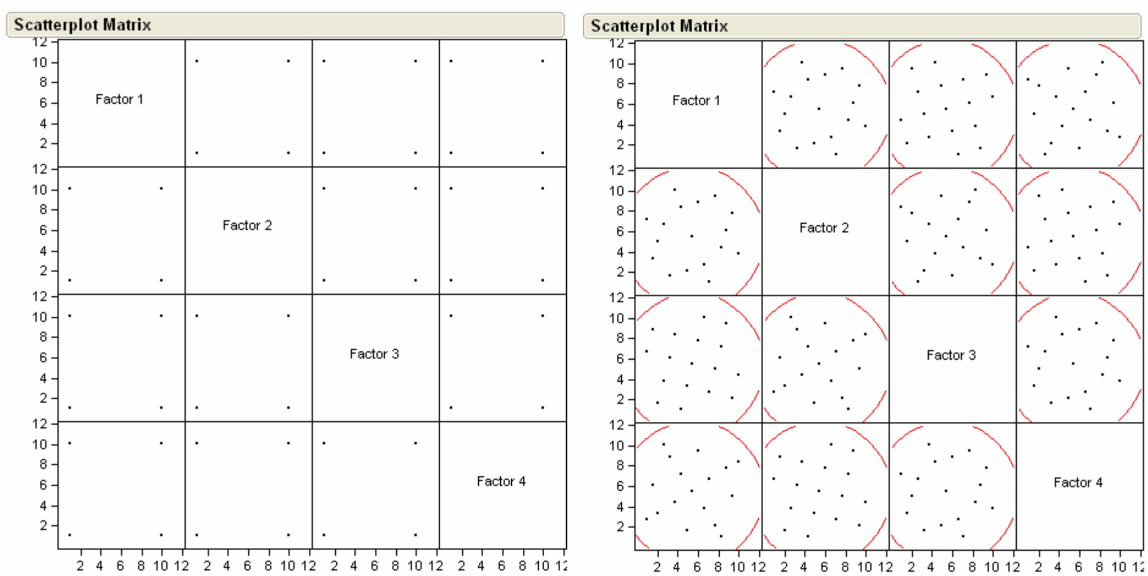

Figure 14. Comparison between 2^k-factorial design and NOLH with 4 factors.

16 This design uses the spreadsheet available at http:/harvest.nps.edu/ <Software Download>.

The 2^k-factorial design covers only the corners, while the NOLH fills the space without touching the extreme points in the corners. Both designs are orthogonal, as shown in the correlation matrices (Figure 15).

2^k-factorial Design

Correlations

	Factor 1	Factor 2	Factor 3	Factor 4
Factor 1	1,0000	0,0000	0,0000	0,0000
Factor 2	0,0000	1,0000	0,0000	0,0000
Factor 3	0,0000	0,0000	1,0000	0,0000
Factor 4	0,0000	0,0000	0,0000	1,0000

NOLH Design

Correlations

	Factor 1	Factor 2	Factor 3	Factor 4
Factor 1	1,0000	0,0000	0,0000	0,0000
Factor 2	0,0000	1,0000	0,0000	0,0000
Factor 3	0,0000	0,0000	1,0000	0,0000
Factor 4	0,0000	0,0000	0,0000	1,0000

Figure 15. Comparison of the correlation matrices of a 2^k-factorial design and NOLH design.

The only noticeable disadvantage of a NOLH design is the lack of coverage at the edges. Extreme low and high settings for input factor combination are not achievable with this kind of design. The next section, which deals with uncontrollable factors, shows a solution to cover the edges.

B. NOISE FACTORS

The introduction of uncontrollable factors, also called noise factors, is necessary to examine the impact of communication aspects on a broader base. The enemy's behavior and capabilities affect outcomes, but are outside of blue control. Modeling them explicitly, but classifying them as noise factors, allows the experimenter to test the robustness of proposed solutions. All controllable combinations of the communications aspects are tested in several scenarios with different noise factor settings, such as the density of blockades.

The number of blockades per wave is directly controlled by the number of super-agents associated with the wave. In a first approach, a NOLH design for the noise factors is examined. The use of the NOLH Excel spreadsheet leads to a DOE with 17 design points. Table 2 presents the chosen ranges. A large range has been chosen to stress the

communication factors. Although it is clear that 15 blockades, the upper bound, is an unrealistically high number, the range is designed to also explore results for a more reasonable number of blockades.

	Number of Agents		Resulting Blockades per Wave	
	Max	Min	Min	Max
SuperAgent 11	11	7	1	5
SuperAgent 22	14	10	1	5
SuperAgent 33	17	13	1	5
Wanted Total number of Blockades			3	15

Table 2. NOLH settings for the super-agents and the resulting blockade outcomes.

The actual resulting range for the total number of blockades is 5 to 12. The NOLH-design does not explore the values below five and greater than 12. These ranges are also important, however. Therefore, eight new design points are attached: one setting for achieving 15 blockades and seven settings to fill the space below five. These seven settings are derived by taking one blockade per wave. The complete Excel spreadsheet is contained in Appendix Table 4. The distribution of the resulting blockades is shown in Figure 16.

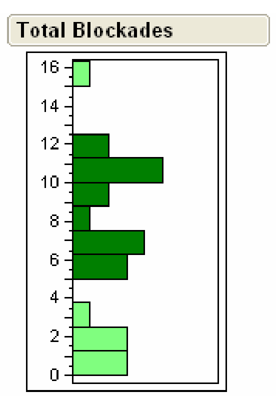

Figure 16. The distribution of the resulting numbers of blockades. The marked parts are the NOLH-elements.

The additional design points adversely affect the orthogonality of the design. As visualized in the correlation matrices in Figure 17, the entries above and below the main diagonal are about 0.5, which clearly differs from 0. The correlation matrix for the pure NOLH is given as a comparison, where the absolute values of the off-diagonal entries are negligible. The differences in correlation occur when the numbers are rounded to integers.

Correlations

	SuperAgent11	SuperAgent22	SuperAgent33
SuperAgent11	1,0000	-0,0805	-0,0085
SuperAgent22	-0,0805	1,0000	-0,0085
SuperAgent33	-0,0085	-0,0085	1,0000

Correlations

	SuperAgent11	SuperAgent22	SuperAgent33
SuperAgent11	1,0000	0,4956	0,5271
SuperAgent22	0,4956	1,0000	0,5271
SuperAgent33	0,5271	0,5271	1,0000

Figure 17. The correlation matrix for the pure NOLH (left) and the combined design (right).

The disadvantage is acceptable because this design is crossed with another NOLH-design. Each design point is combined with each design point of the other design. The correlation within one of the designs does not affect the result of the Cartesianly joined design. The resulting combinations are mutually orthogonal. The correlation matrix for a crossed design is detailed later in this thesis.

C. CONTROLLABLE FACTORS

The controllable factors in this research are parameters that directly or indirectly influence the blue force communication capabilities and are controllable by the blue forces. This thesis explores seven factors of the scenario. These factors are defined in the following section. Attributes for the sensor grid are changed simultaneously for all

squads in a lock-stepped mode. Instead of increasing the number of factors, the lock-stepping is scripted in the XML[17] study-file created by a special software tool called Tiller.[18]

The first six factors of the scenario in question are physical parameters of the sensor grid agents. The last factor is a parameter directly affecting the convoy. When possible, the MANA definition found in the User's Manual[19] is given or an explanation is provided as to how this factor was created in the scenario.

- *Latency:* (MANA definition) Number of time steps taken for each message to reach the squad.
- *Reliability:* (MANA definition) Likelihood that a given message will be successfully sent on a link per try. Repeated attempts are made at resending unsuccessful messages until they are successfully communicated.
- *Capacity:* (MANA definition) Number of messages that can be sent through the link per time step. This factor corresponds to the bandwidth in real world terms. Due to the workarounds, the number of messages is not linear to the number of agents on the battlefield. This factor allows for assessment of effects and interactions, but a one-to-one mapping is not possible.
- *Pause duration between Updating:* This factor describes the amount of time the sensor grid pauses before sending an update. MANA does not provide a direct data entry; therefore, a workaround is created that effectively blinds the sensor for the pause duration.
- *Communication range:* Maximum range between the centroid of the transmitting and receiving squads. The communication range as a factor is only applied in the design for assessing the model's behavior, and varies in binary style (0 m vs. 2000 m). This factor is used as surrogate for whether or not a communication link is available.

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17 The definition for XML comes from www.wikipedia.org: "The Extensible Markup Language (XML) is a W3C-recommended general-purpose markup language that supports a wide variety of applications. XML languages or "dialects" are easy to design and to process.... Its primary purpose is to facilitate the sharing of data across different information systems, particularly systems connected via the Internet."

18 The Tiller is a software-tool provided by Project Albert to connect the scenario with the DOE. Based on the MANA scenario, the input factors and their ranges are entered and the kind of design is chosen. The software will automatically create a study including the DOE. This folder contains the scenario XML-file, the terrain and the XML-study file. The study file can be used directly by the high performance computer.

19 MANA Version 3.0 Users Manual, D. Galligan, M. Anderson, M. Lauren, July 2004.

- *Sensor range:* (MANA definition) The radius in cells in which an agent can detect and classify targets.
- *MaxAge (Inorganic threat Persistence):* (MANA definition) The number of time steps that must pass before a contact on the squad inorganic situational awareness disappears. MaxAge is set at 1.5 * Latency. This means that, at the minimum, the contact remains on the map for the delay time in the network; the contact may also stay an additional time. When a contact is on the map, it may influence an agent's decision.

All seven controllable factors of the scenario are designed to provide insights about communication aspects in urban terrain. Their input ranges are outlined in the Table 3.

	MANA Scenario		Real World	
	Lower	Upper	Lower	Upper
Latency	50	500	6 sec	60 sec
Reliability [%]	10	100	10	100
Capacity	300	500	Not directly convertible	
Pause between Updates	20	200	2.5 sec	25 sec
Sensor Range	300	500	300 m	500 m
MaxAge	Lockstep function: 1.5 * Latency			

Table 3. Input factor ranges.

With the exception of MaxAge, all of these factors are entered in the spreadsheet for creating the NOLH design. In this case, a 65 design point NOLH has been chosen to achieve a dense spread. The map clearing frequency is added in the spreadsheet later as an extra column.

D. DESIGN FOR ASSESSING THE MODEL QUALITY

The experiment explained in the following section tests the model in order to explore the influence of MANA limitations on the scenario discussed in this thesis.

To gain insights, two different scenarios were established for this design of experiment (DOE). The first scenario excludes the communication aspects between the

sensor grid and the convoy. In other words, the convoy has only visually collected information available. On the other hand, the convoy can rely on perfect information in the second scenario. In this case, perfect information is given by a latency of zero time steps, a reliability of 100 percent, capacity of 500 messages per time step, pauses between updates of 10 time steps, and a sensor range of 350m for the sensor grid. .

The DOE is set up by crossing the noise settings (25 design points) with a binary communication range for the sensors (0m and 2000m). The change for the communication range is lock-stepped for all five sensors in the grid. The DOE conducts 100 replications for each of the 50 design points.

There are several ways to eliminate communication in the scenarios. This experiment alters the physical settings of the sensor grid instead of disabling the agents themselves in the scenario. A change in the number of agents placed on the battlefield would result in a different blockade setting for a seed used in the run with and without communications. Therefore, the pair-wise comparability would get lost. Although it is also possible to set the inorganic desires of the convoy to 0, this method requires several changes—specifically, the involvement of 2 trigger states and 3 desires.

A fixed set of 100 seeds[20] guarantees that each seed provides the same blockade setting, given the same number of super agents, but independent from the communication settings. Because of this fact, runs with and without communication are directly comparable in the analysis phase. The paired t-test, the most powerful tool for comparing means of two normal samples, is applicable, as Chapter IV will make evident.

E. DESIGN FOR EXPLORING COMMUNICATION ASPECTS

This section explains the design to capture the impact of communication factors. As mentioned, this test employs a crossed design using the controllable and uncontrollable factors. Each design point of the noise factors is tested against each

20 The Tiller software generates a set of 100 seeds. The set is applied to all design points. This means that replication #1 on design point #1 has the same seed like replication #1 on design point #2.

design point of the controllable factors. The broad approach ensures that the experimenter may distinguish between factors that dominate the scenario and factors that can be ignored in further experiments.

The crossed design consists of 1625 design points, each with 100 replications. The correlation matrix in Figure 18 shows that there is no correlation between the noise and controllable factors (see box). As a result, useful properties for the analysis are provided. This matrix also shows the strong correlation between the factors Latency and MaxAge, the linear function of Latency (see oval). Instead of presenting the level of the super agents, which are varied, the number of resulting blockades is used to calculate the correlation matrix. The number of blockades is achieved by a linear transformation of the number of associated super agents. Therefore, the correlations among the blockades are identical to the correlations among the super agents.

Correlations

	Blockade A	Blockade B	Blockade C	Latency	Reliability	PAUSE duration	SENSOR Range	Capacity	MaxAge
Blockade A	1,0000	0,4956	0,5271	-0,0000	-0,0000	0,0000	-0,0000	0,0000	0,0000
Blockade B	0,4956	1,0000	0,5271	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
Blockade C	0,5271	0,5271	1,0000	-0,0000	-0,0000	-0,0000	-0,0000	0,0000	-0,0000
Latency	-0,0000	0,0000	-0,0000	1,0000	-0,0013	0,0008	0,0005	-0,0008	1,0000
Reliability	-0,0000	0,0000	-0,0000	-0,0013	1,0000	-0,0031	0,0006	0,0007	-0,0013
PAUSE duration	0,0000	0,0000	-0,0000	0,0008	-0,0031	1,0000	0,0003	0,0001	0,0009
SENSOR Range	-0,0000	0,0000	-0,0000	0,0005	0,0006	0,0003	1,0000	-0,0002	0,0004
Capacity	0,0000	0,0000	0,0000	-0,0008	0,0007	0,0001	-0,0002	1,0000	-0,0008
MaxAge	0,0000	0,0000	-0,0000	1,0000	-0,0013	0,0009	0,0004	-0,0008	1,0000

Figure 18. The correlation matrix for this communication aspect design. By crossing the two designs Cartesianly, orthogonality is obtained between controllable and uncontrollable factors, even when there is correlation among factors within each design.

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IV. DATA ANALYSIS

This chapter focuses on data processing and data analysis. It provides information about the software package that is used and statistical tools that are applied to gain insights from the model. The next section describes how the raw data is cleaned up and prepared for the analysis. In the first analysis part, two important questions are raised:

- How well is the model doing?
- How reliable is the model in examining the focus of the research?

The answers allow drawing conclusions about the usefulness of modeling a scenario like this in MANA by choosing an approach similar to that of the author. Finally, the main experiment is analyzed and the results are presented.

A. STATISTICAL SOFTWARE PACKAGE JMP

To conduct an analysis on a large data set a professional statistical software package is necessary. The author considered several packages and decided to use JMP The Statistical Discovery Software™. In the manual, the software developers state that JMP is easy to learn.[21] The author agrees on this point and is convinced of its user friendly appearance. Some advantages experienced while working with JMP are briefly summarized:[22]

- GUI interface for all activities.
- Spreadsheet features for manipulating large data sets.
- A broad range of graphical and statistical methods for data analysis.
- Capability of grouping data and computing summary statistics.
- Tools for printing and moving analysis results between applications.

JMP provides the entire tools necessary for the discovery tour through the data sets in this thesis research.

21 JMP The Statistical Discovery Software, Introductory Guide Version 5.

22 JMP The Statistical Discovery Software, Introductory Guide Version 5.

B. RAW DATA POSTPROCESSING

The raw data returned by the Maui High-Performance Computer Center (MHPCC) consists of two types. One is an EXCEL file containing the factor levels and various squad outputs, e.g., the number of casualties or injuries. This file can directly import into JMP and be manipulated within the software tool. The other data collected are the agents' end data for each run. In order to extract the main entries, a small Ruby program (see Appendix Figure 36) was written and applied. This tool reads in each file and puts the important facts, i.e., number of hits and final location of the convoy, in an extra text file.

The JMP software package has good spreadsheet characteristics, as mentioned in the previous section. In the next step the columns of the csv file and the columns of the text file are joined. However, only a few of the more than hundred columns are interesting and necessary for this research thesis. Hence, the others are deleted.

Data entries are converted and the following new columns are added in order to achieve more readability.

- New column: The number of super agents per wave is translated into blockades per wave.
- New column: The mission length is calculated by subtracting 100 time steps from the scenario run time due to the setting phase which was explained in Chapter II.
- New columns: All time step measures are converted into seconds. This is done for all factors and results.

As mentioned in Chapter II, the MOEs are the mission length, the number of hits, and the number of broken blockades. The last one is the sum of three columns, specifically the number of injured blockades. Also calculated is the total number of blockades.

C. STATISTICAL METHODS

After preparing the data set the tools used to gain insights are briefly introduced. The analyst's tool bag consists of graphical tools, parametric and non-parametric procedures, multiple regression, and regression trees.

1. Graphical Analysis

A commander believes more of what he sees than what he is told. Following this common staff slogan, the data is analyzed with simple graphical tools, e.g., histograms. Graphs and plots provide the first impression about some insights and ease the interpretation and explanation, especially to higher ranking officers without detailed knowledge about analysis techniques.

2. Parametric and Non-parametric Procedures

Parametric procedures are based on distributional assumptions. The most common parametric tests require normality, i.e., nice bell-shaped behavior in the data or at least for the estimators. On the other hand, non-parametric procedures are often referred as "distribution-free."[23] The data analysis in this research uses the paired t-test as a member of the parametric procedures and the Shapiro-Wilk W-test from the non-parametric procedures.

- The verification experiment delivers paired data. The paired t-test is conducted to investigate whether the two samples could have the same mean. The test requires independent and normally distributed sample means.[24] Fortunately, the t-test is robust against non-normally distributed data for large sample sizes. The paired t-test focuses on means. The Central Limit Theorem states that the sample mean is approximately normally distributed given a sufficiently large sample size.[25]
- The Shapiro-Wilk W-test[26] is a "distribution-free" procedure. The Shapiro-Wilk W-test examines the hypothesis that the sample comes from a normal population.

3. Regression Trees

A regression tree is a Data Mining[27] technique. "There is no implicit assumption that the underlying relationships between the predictor variables and the dependent

23 Jay L. Devore, "Probability and Statistics," 6th Edition, 2004, p. 667.

24 Jay L. Devore, "Probability and Statistics," 6th Edition, 2004, p. 381.

25 Jay L. Devore, "Probability and Statistics," 6th Edition, 2004, p. 239.

26 W.J. Conover, "Practical Nonparametric Statistics," 3rd Edition, 1999, p. 450. If the test statistics W "is close to 1.0 the sample behaves like a normal population." If W "is too small and far below 1.0, the sample looks non-normal."

27 David Hand, "Principles of Data Mining," 2001, p. 2, Definition: "Data mining is the analysis of (often large) observational data sets to find unsuspected relationships and to summarize the data in novel ways that are both understandable and useful to the data owner."

variable are linear, follow some specific non-linear link function, or that they are even monotonic in nature."[28] More advantages of this assumption-free tool are listed in the JMP help as follows:

- "it is good for exploring relationships without having a good prior model
- it handles large problems easily, and
- the results are very interpretable."[29]

The regression tree method is applied to a continuous response variable and input factors which can be continuous or categorical. The tree structure is built by binary recursive partitions. The goal is to minimize the sum of squared deviations within the separated groups. This process increases the "purity" in the class.[30] The sequence of factors involved in partitioning allows drawing conclusions on their importance. Consecutive splits in a branch where different factors are involved may indicate an important interaction. Another combination, i.e., one factor showing up twice in a row may be an indication of a non-linear effect. The analyst gets an idea on a potential linear regression model. On the other hand, factor levels are noticeable when a split occurs. In some cases, when a significant improvement is noticed, this factor level can be interpreted as a threshold.

4. Multiple Linear Regression

"Regression analysis is one of the most widely used techniques for analyzing multifactor data."[31] In this thesis, multiple linear regression analysis is applied. It deals with one continuous response and continuous and categorical input factors, called predictors or regressors. The response is a linear combination of coefficients of predictors and an additive statistical error. This error is often assumed to be uncorrelated and normally distributed with mean 0 and constant variance.

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28 StarSoft Technologies, www.statsoft.com/textbook/stcart.htm, December 2006.

29 JMP 5.2.1 online-help Index "Partition."

30 David Hand, "Principles of Data Mining," 2001, p. 343.

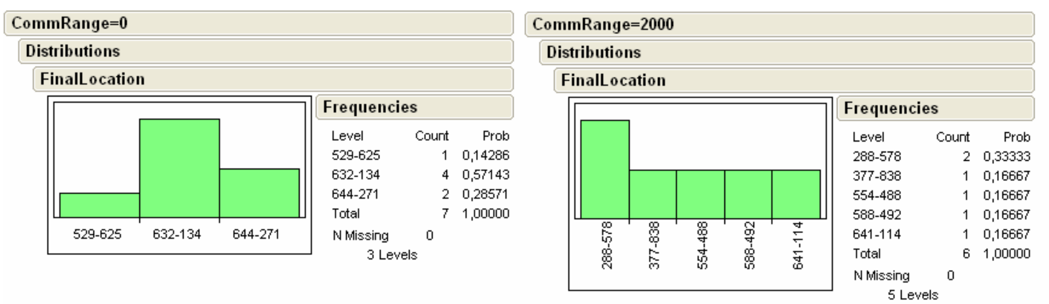
31 Douglas C. Montgomery," Introduction to Linear Regression Analysis," 3rd Edition, 2001, p. xiii.

Regression models are useful to describe data, estimate parameters, predict and estimate outcomes. Of course, agent-based models are not built for prediction purposes, as the author mentioned in Chapter II. In this thesis, regression models are used to gain insights about the important factors and their interactions.

D. ANALYSIS FOR ASSESSING THE MODEL'S QUALITY

1. Unfinished Runs

One technique to consider on whether this model is doing a "good" job is a look at the runs and which of them are terminated by the time limit. Occasionally, the convoy gets "stuck" along the way. This would never happen in the real world. Within the data set of 5000 runs, only in 13 cases (0.28 %) did the convoy not reach the final destination—that is, it got stuck on its way. Figure 19 shows the distribution of the last location on the map as a function of the communication range.



Level	Count	Prob
529-625	1	0,14286
632-134	4	0,57143
644-271	2	0,28571
Total	7	1,00000
N Missing	0	
3 Levels		

Level	Count	Prob
288-578	2	0,33333
377-838	1	0,16667
554-488	1	0,16667
588-492	1	0,16667
641-114	1	0,16667
Total	6	1,00000
N Missing	0	
5 Levels		

Figure 19. Distribution of the final locations split by the communication range.

The author re-ran some scenarios and noticed that these final locations result from terrain issues. Mostly, the terrain around the last location is not smooth enough to allow the convoy to move on.

Due to the fact that at most two runs per design point are terminated by the time limit, the author evaluates their occurrences as non-critical and leaves them within the data set.

2. MOE Selection

In this first approach, the author decided to get a broad overview on the simulation outcome by looking at the combined correlation matrix, including the input factors and MOEs. The first question is whether communication has any impact on the outcome. In this experiment, the communication range has two levels, 0 and 2000, which can be translated as having and not having communication. In the former case the convoy can take advantage of getting perfect information without latency.

The blue box in Figure 20 indicates that having communications increases mission length (positively correlated), decreases the number of broken blockades and the number of hits (both negatively correlated). The way communication affects the outcome fulfills the author's expectations. The levels do not show a strong correlation (near -1 or 1), but they differ noticeably from zero.

Correlations

	Blockade A	Blockade B	Blockade C	CommRange	Mission Length	Broken Blockades	#HITS
Blockade A	1,0000	0,4956	0,5271	0,0000	0,1133	0,2424	0,4205
Blockade B	0,4956	1,0000	0,5271	0,0000	0,2141	0,2224	0,4381
Blockade C	0,5271	0,5271	1,0000	-0,0000	0,2024	0,2546	0,3955
CommRange	0,0000	0,0000	-0,0000	1,0000	0,2088	-0,1348	-0,1980
Mission Length	0,1133	0,2141	0,2024	0,2088	1,0000	0,2291	0,3915
Broken Blockades	0,2424	0,2224	0,2546	-0,1348	0,2291	1,0000	0,5024
#HITS	0,4205	0,4381	0,3955	-0,1980	0,3915	0,5024	1,0000

Figure 20. This correlation matrix shows the impact of having communication for the MOEs (blue box) and the correlation among the MOEs which makes a pre-selection possible. (Best viewed in color)

The red box in Figure 20 demonstrates the correlation among the MOEs. Obviously, the three MOEs are correlated. The correlation between "Broken Blockades" and "#Hits" reaches 0.5. This is meaningful due to the fact that fighting through the blockades is only possible for the convoy within a 25 meter radius of the blockade. This is the range in which the blockade has its highest probability of hit. The other correlations, including with mission length, are clear, but not so strong. However, all correlations are positive. This means that examining one MOE deeply provides

information about the other two MOEs. In this case, the author's focus lies on the number of hits the convoy gets. Nevertheless, the analysis on the other two MOEs is also conducted. The results, only briefly mentioned here, are not consistent. In a leap ahead, the p-values for the paired t-test on the two samples for each MOE do not stay below the given level of significance of 0.05. This means that at some design points the means for one MOE with and without communications are different, but they are not statistically different. There remains the chance that both samples are from populations with the same mean at the given design point. The most dangerous elements in combat situations are the bullets. In the author's opinion, the number of hits is the most important measure, which is also the only statistically consistent MOE in this simulation.

3. "Measuring" the Impact of Communications

This section deals with the question of how well the model behaves. The experimental setup allows comparing two runs with the same blockade setting and different communication parameter settings. Referring to the MOE selection, the author uses only the number of hits for examining the impact of communication. Within JMP, a data table is created that contains the needed parameter information and the number of hits with communication and the number of hits without communication in one row. In the next step, the differences between the number of hits without and without communications are calculated. A negative value means that the convoy with communications suffers more hits than the one without communications. In addition, columns are attached containing binary indicators of whether the runs with communication ended with a lower or equal number of hits. Instead of regarding each run, a summary table is created which contains the parameter setting, the mean of the differences, and their standard deviations for each design point.

At first, the variability is checked with a box plot containing all design points. This is done in Figure 21 below.

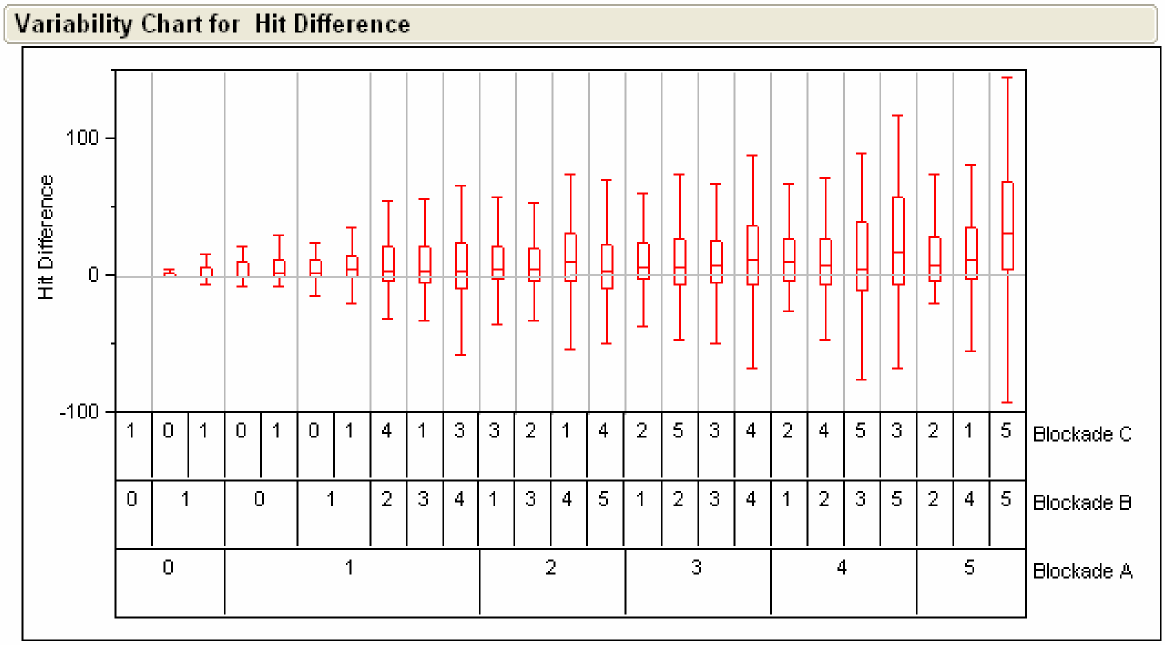


Figure 21. The variability for each design is demonstrated in this range plot.

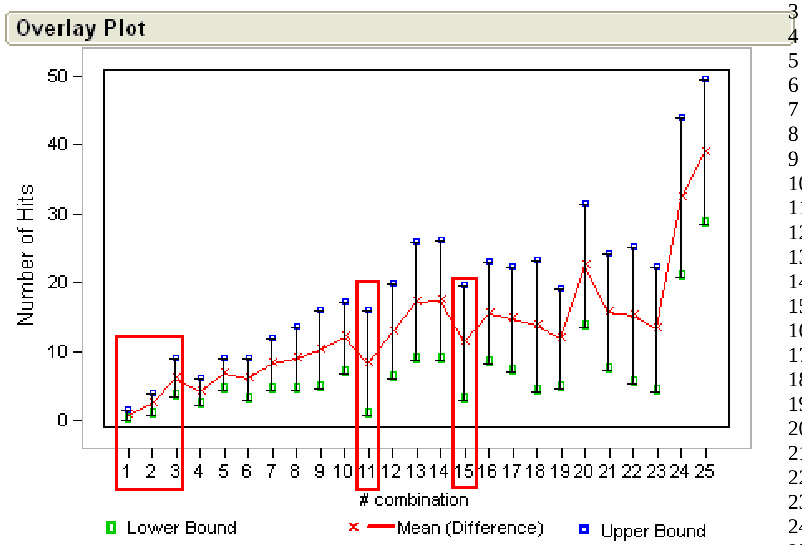
The extracted data contains a lot of variability. Especially, the large negative amplitudes are an indicator that the situation is inherently highly variable. Agent-based models are stochastic models and therefore they incorporate randomness. Small negative amplitudes could have been caused by this effect. All 25 means are positive and with more blockades showing they are clearly distinguishable from zero. Under the hypothesis that communications have no effect on the outcome, the chance of observing fewer hits (i.e., positive median hit difference) at all design points, has the probability of $(½)^{25}$ $(=3*10^{-8})$ if the design points are uncorrelated. An empirical test shows that the correlations among these 25 samples are consistent with correlations among 25 normally distributed random samples. Therefore, on the whole, communications help the convoy, especially with increasing difficulty level. Some scenarios were re-run in order to find the true story behind these large negative differences. The main causes are summarized:

- The convoy with communication gets stuck in a position where it is exposed to hostile fire. The convoy without communications does not stop due to its different desires and route.
- The occurrence of an unlucky event is also observed. The convoy with perfect knowledge avoids blockades in the first wave but it is caught by an ambush in the second wave while the convoy without communications

gets hits but luckily its later route is safer without any ambush situation. Of course, this could happen in the real world.

- In some cases the convoy with additional inorganic information does not behave like a human being. Driven by its weights it ignores the grid friends' and helpers' signals and runs straight into the blockade, or, even worse, into an ambush where fire hails on it.

The first analysis is an eye opener of the model's performance. It is obviously not perfect, but the question is how "good" or useful is it. This question is examined by taking a closer look at the means. The means and the 95%-confidence interval for all 25 design points are shown graphically in Figure 22.

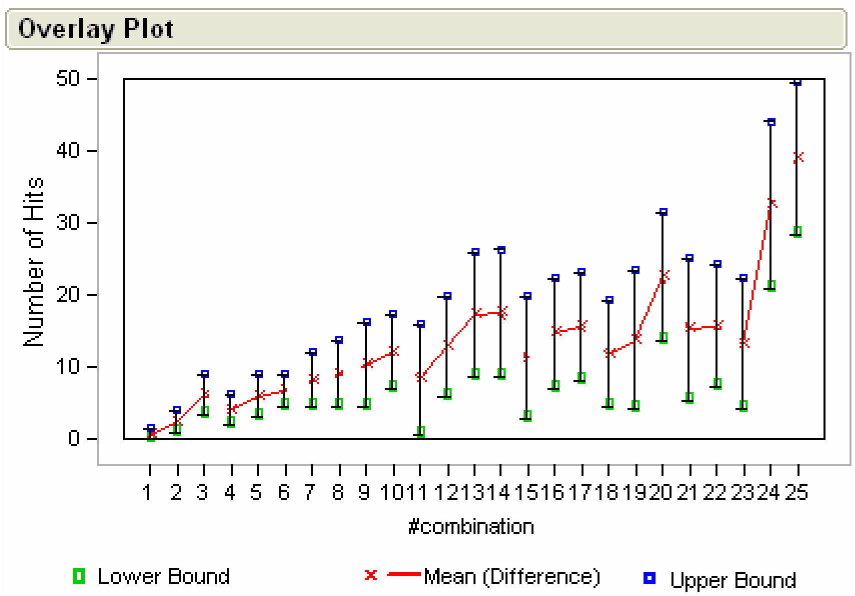


1	0-0-1-(1)
2	0-1-0-(1)
3	1-0-0-(1)
4	0-1-1-(2)
5	1-0-1-(2)
6	1-1-0-(2)
7	1-1-1-(3)
8	1-3-1-(5)
9	2-1-3-(6)
10	3-1-2-(6)
11	1-2-4-(7)
12	2-3-2-(7)
13	2-4-1-(7)
14	4-1-2-(7)
15	1-4-3-(8)
16	3-3-3-(9)
17	5-2-2-(9)
18	3-2-5-(10)
19	4-2-4-(10)
20	5-4-1-(10)
21	2-5-4-(11)
22	3-4-4-(11)
23	4-3-5-(12)
24	4-5-3-(12)
25	5-5-5-(15)

Figure 22. The means of the differences and 95%-CI for all 25 design points (#combination). The blockade setting is listed beside [A-B-C-(Total)]. (Best viewed in color)

The graph indicates the main trend that an increasing number of blockades results in larger differences. The first box shows that 1 blocked street in wave A (combination 3) has a larger impact on the difference than the two previous ones due to a lack of alternative routes at the starting point. The drops (11 and 15) occur because the number of blocked roads (wave A) decreases in comparison to the previous design points. This indicates that the number of blocked streets at the beginning strongly influences the

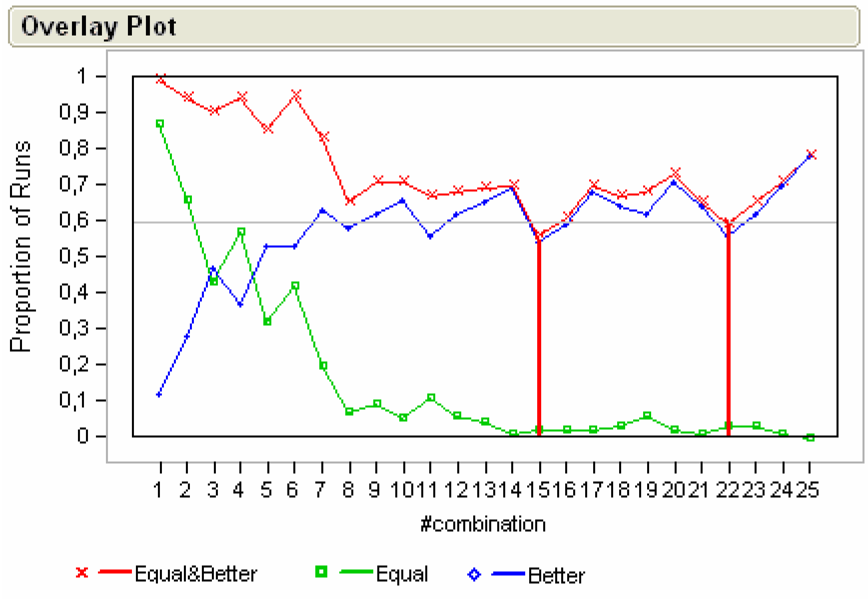
outcome. The density of blockades in the first wave is higher. In order to illustrate this result the same plot is shown after reordering the design points within the number of total blockades (see Figure 23). The ordering can be interpreted as difficulty levels within one group of design points having the same number of resulting blockades. Looking at the combinations 23 and 24, it can be concluded that the setting 4-5-3 is harder than 4-3-5. The argument holds that the blockade density in wave B is higher than in wave C.



1	0-0-1-(1)
2	0-1-0-(1)
3	1-0-0-(1)
4	0-1-1-(2)
5	1-1-0-(2)
6	1-0-1-(2)
7	1-1-1-(3)
8	1-3-1-(5)
9	2-1-3-(6)
10	3-1-2-(6)
11	1-2-4-(7)
12	2-3-2-(7)
13	2-4-1-(7)
14	4-1-2-(7)
15	1-4-3-(8)
16	5-2-2-(9)
17	3-3-3-(9)
18	4-2-4-(10)
19	3-2-5-(10)
20	5-4-1-(10)
21	3-4-4-(11)
22	2-5-4-(11)
23	4-3-5-(12)
24	4-5-3-(12)
25	5-5-5-(15)

Figure 23. Reordered plot showing the means of the differences and 95%-CI for all 25 design points (#combination). Means in the same group are connected. The blockade setting is listed beside [A-B-C-(Total)]. (Best viewed in color)

All of the means on the differences are positive. Having communications reduces the expected number of hits. If not, the chance of seeing this is a rare event. This implies that the model does a “good” job on average. To gain more insights, the proportions of runs which do better with communication are examined. The graph in Figure 24 demonstrates the proportions for each design point. The ordering of the design points remains as found in the previous section.



1	0-0-1-(1)
2	0-1-0-(1)
3	1-0-0-(1)
4	0-1-1-(2)
5	1-1-0-(2)
6	1-0-1-(2)
7	1-1-1-(3)
8	1-3-1-(5)
9	2-1-3-(6)
10	3-1-2-(6)
11	1-2-4-(7)
12	2-3-2-(7)
13	2-4-1-(7)
14	4-1-2-(7)
15	**1-4-3-(8)**
16	5-2-2-(9)
17	3-3-3-(9)
18	4-2-4-(10)
19	3-2-5-(10)
20	5-4-1-(10)
21	3-4-4-(11)
22	**2-5-4-(11)**
23	4-3-5-(12)
24	4-5-3-(12)
25	5-5-5-(15)

Figure 24. Comparison between runs with and without communications showing the percentage of how many runs have less hits, equal number of hits and the combined measure. The blockade setting is listed beside [A-B-C-(Total)]. (Best viewed in color)

Two main trends are observable in Figure 24. The green line (□) describes the proportion of runs with the same outcome. In a low threat scenario, e.g., for one blockade model, most runs have the same outcome. Increasing the threat level causes the equal outcomes to decrease. On the other hand, the proportion of runs where communications have a strictly positive influence (◊) on the result is increasing at the same time. The sum of both (x) has been chosen as a measure of the model quality.

Due to the high variability, the performance drops down below 70% and stays in this region. Two dips in this nearly horizontal line are remarkable—in fact the performance decreases below 60%. The points have one common pattern. At the beginning the convoy experiences a low intensity phase which is followed by a massive appearance of blockades in the wave B.

The lack of performance will be discussed again at the end of this Chapter when the author summarizes the findings and evaluates the quality and usefulness of the model.

After the graphical examination of the data, a sequence of statistical tools is applied to analyze whether the two samples (with and without communication) are from different populations. The test procedure is conducted on one design point for demonstration purposes. The entire results are listed in the Appendix Figures 37 to 43.

The distribution of the hit differences are created for each design point in JMP. As mentioned before, the paired t-test can be applied even when the underlying distribution is not bell-shaped normally distributed. A large sample size guarantees, by the Central Limit Theorem, that the mean is roughly normally distributed. This allows using standard techniques to examine the mean.

The author decided to check on normality as well before using the t-test. Therefore, a fitted normal distribution provided by JMP is included (see Figure 25).

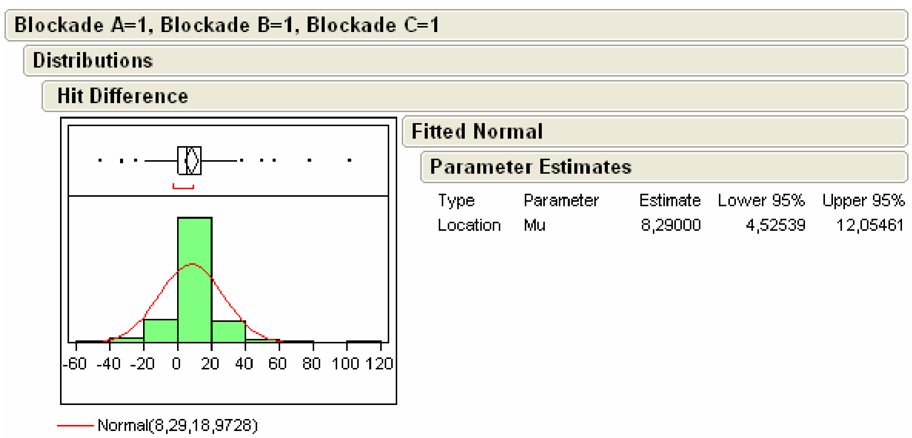


Figure 25. The distribution of the hit difference for a specific blockade setting and its fitted normal distribution.

The distribution seems be bell-shaped around the mean, but the asymmetric behavior towards the edges allows the conclusion that this data is not normally distributed. To confirm this observation a Quantile-Quantile plot (QQ-plot) [32] is

32 Douglas C. Montgomery, “Introduction to Linear Regression Analysis,” 3rd Edition, 2001, p. 192 “Normal Probability plot… . If the sample observations are in fact drawn from a normal population with mean μ and standard deviation σ, the points should fall on a straight line with slope σ and intercept μ. Thus a plot for which the points fall close to some straight line suggests that the assumption of a normal population distribution is plausible.”

examined. Normally distributed data should show up along a straight line. In a parallel approach the Shapiro-Wilk-test is conducted (See Figure 26).

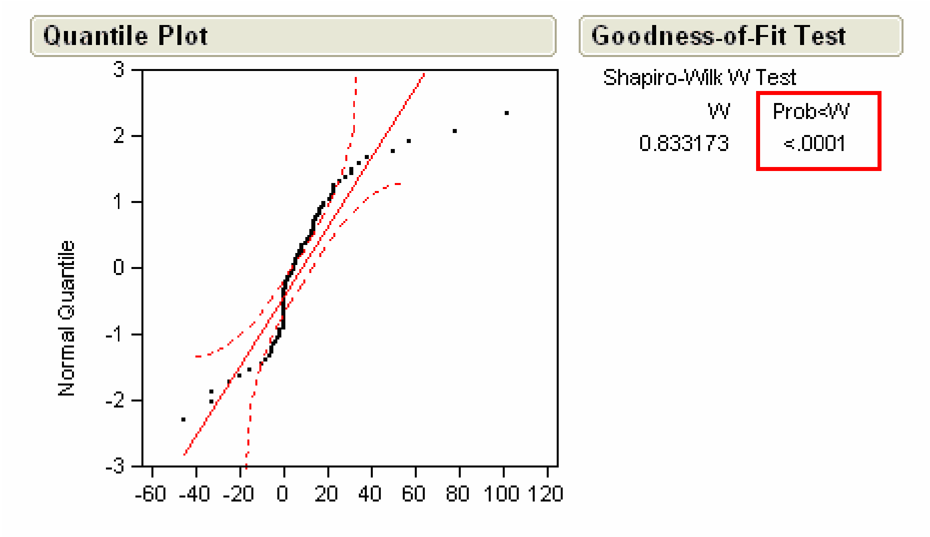


Figure 26. Qantile-Quantile plot showing that the distribution is definitely not normal. This result is confirmed by the Goodness-of-Fit test shown in the box.

Obviously, normality cannot be assumed looking at the plot and the low p-value (Figure 26 red box) provided by the Shapiro-Wilk-test. But the absence of normality does not mean that no further analysis is possible. The t-test has robustness against non-normality, as mentioned in the previous section. A large sample size is necessary to apply it and get reliable results. One hundred runs per design point guarantee a sufficiently large sample size. Actually, due to the sample size, this can be seen as a z-test. JMP provides a GUI to conduct the t- test. The hypothesis under which this paired t-test is conducted is stated in the following way:

$$H_o: \mu_{HitDifference} \leq 0$$
$$H_a: \mu_{HitDifference} > 0$$

Because of the author's intent to work out the improvements by having inorganic information, a one-sided test is preferred and seems to be more appropriate to answer the research question. The result provided by JMP is shown in Figure 27.

Test Mean=value

Hypothesized Value		0
Actual Estimate		8,29
df		99
Std Dev		18,9728
	t Test	
Test Statistic	4,3694	
Prob > |t|	<,0001	
Prob > t	<,0001	
Prob < t	1,0000	

Figure 27. The test result for the paired t-test demonstrates that communications reduces the number of hits.

The p-value is smaller than 0.001. This implies that the hypothesis must be rejected. Actually, communications significantly reduce the expected number of hits which is observed by positive differences. The paired t-test is the most powerful test on two sample means. This sequence of tests is also conducted for the other 24 design points and is shown in Appendix Figures 37 to 43. The results are similar to the explained one.

4. Discussion and Conclusions

Looking at the convoy's behavior with and without communications it seems that the received inorganic information has an impact on the expected number of hits. Having support by a sensor grid implies a reduced number of hits on average. The statistical analysis shows that for all design points both samples have different means. The model does the right thing on average. Its weakness is expressed in the proportion of runs where communications does not positively influence the outcome. On average 30% to 40% (maximum 44%) of the runs ended with a less hits when the convoy does not have a sensor grid support.

This portion sounds high. However, human decision making does not lead automatically to the optimal solution. Sometimes a decision has to be made within seconds. The convoy leader is under combat stress and has time limitations for his decision. In situation like this a human decision-maker relies on heuristics and biases.[33] The perceived information is processed and one or more hypotheses are generated and tested. If one seems adequate it is chosen as a possible course of action. Furthermore,

33 Christopher Wickens, "An Introduction To Human Factors Engineering," 2nd Edition, 2004, p. 162.

the humans tend to stick with their first hypothesis. Therefore, alternatives are underutilized and rejected. This behavior can result in non-optimal decisions. In some cases they are fatal and lead to a large number of causalities. Also, just by chance (i.e., bad luck) a good decision can lead to a worse outcome than a bad decision.

The author is aware of the high variability incorporated. The chance of non-optimal outcomes in a decision-making process is smaller than demonstrated by the model. With this knowledge, the following analysis has to be interpreted with caution and the resulting numbers have to seen more as directions than precise thresholds.

E. ANALYSIS ON COMMUNICATION ASPECTS

This section focuses on the analysis of the main experiment examining the communication factors. The post processed data set (162,500 rows) is large. The variability within the set is enormously high. Regression analysis on the original data leads to small R-square values, which is a measure how much variability is explained by the regression model. Therefore, the author decided to use the summary data. The data is grouped by design points. The means and standard deviations on the MOEs are calculated and represented in columns. The data set still contains 1,625 elements. The author excluded the factor MaxAge because it is linearly dependent on Latency. A pair of linearly dependent regressors causes multicollinearity in the regression model; this would degrade the quality of the regression model.

1. Pre-Analysis

This section focuses on two pre-tests. Similar to the previously conducted analysis, the runs are examined in the case where the convoy did not accomplish its mission. Following this, the correlation among the MOEs is analyzed.

a. Unfinished Runs

The unfinished runs are extracted. Their distribution is shown in Figure 28.

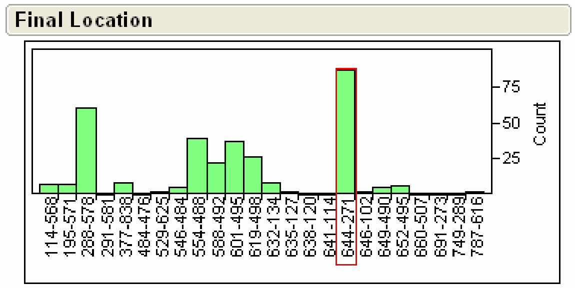


Figure 28. The distribution of the final location.

The distribution chart shows that 24 locations are involved. The author re-ran some of them. One location has a remarkable count. Location 644-271 (red box) contains 88 runs with one common seed. These runs are unfinished due to terrain issues. Following the argumentation in section D1, the convoy gets stuck. The surrounding terrain is not smooth enough to allow the convoy to move on.

b. MOE Selection

The correlation among the 3 MOEs is checked in advance in order to reduce the number of MOEs to be tested. The correlation matrix below (Figure 29) demonstrates that in this experiment a very strong positive correlation exists among all MOEs.

Correlations

	Mean(Mission Length (real))	Mean(Blockades Broken)	Mean(#HITS)
Mean(Mission Length (real))	1,0000	0,6631	0,7190
Mean(Blockades Broken)	0,6631	1,0000	0,9431
Mean(#HITS)	0,7190	0,9431	1,0000

Figure 29. The correlation matrix shows that the MOEs are strongly correlated.

In comparison to the previous experiment, these correlations are powerful (near 1). Being consistent, the number of hits is chosen as the main MOE. However, in this case, the author did not do any analysis on the rejected MOEs.

2. Regression Tree with Noise Factors and Communication Factors

In this first approach a regression tree is used to gain insights into the relationships between the factors. The regression tree does not require any assumptions in order to be applied. The tree structure is shown in Figure 30. Additionally, the factors

involved in splitting are repeated in order to increase the readability. In this step the split levels and resulting group means and standard deviations are less important than the factor itself.

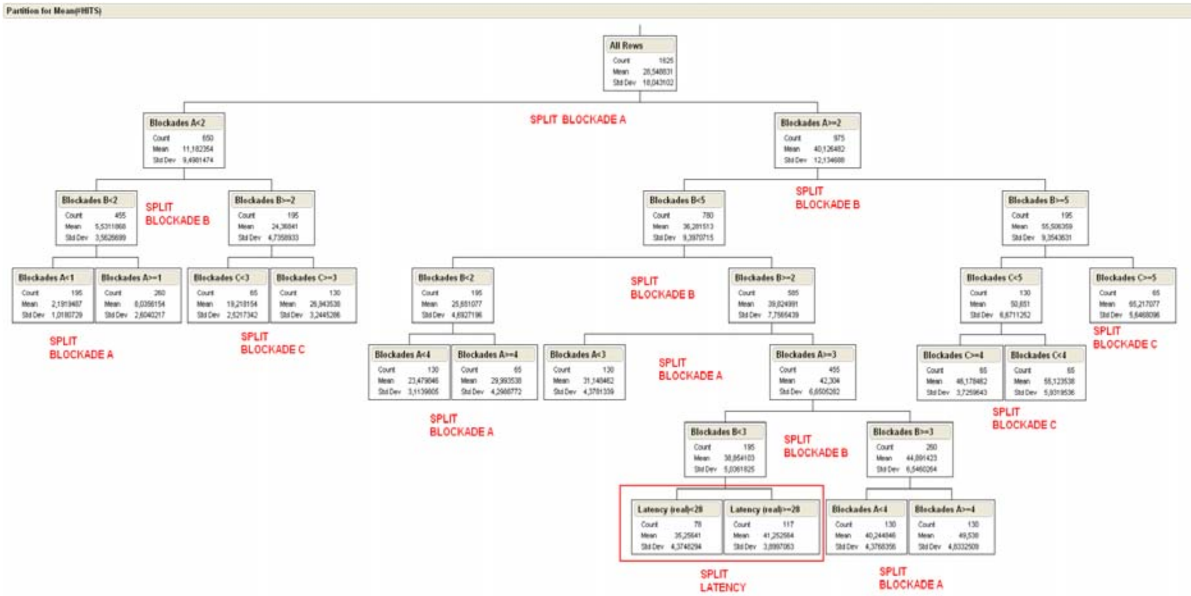


Figure 30. Regression tree on the Mean(#Hit) with all input factors. The first 12 steps are noise factor splits. The first communication factor that shows up is Latency (see red box).

The presented regression tree consists of 13 splits. At the top the “root” of the tree contains all 1625 observations. The first 12 partitions involve exclusively the noise factors. It can be concluded that the blockades (i.e., the enemy behavior), are the major driving factors in this simulation. Looking at the sequences, it becomes obvious that the blockades have a non-linear impact on the outcome. Also, there are most likely interactions among the noise factors. The first communication factor appears in the form of Latency, at the step 13. This indicates the importance of Latency in the simulation. That is, the convoy needs timely information.

These findings are used to frame the next analysis part, where a regression model is derived that includes quadratic terms and two-way interactions among all predictors.

3. Full Regression Model

To achieve a full regression model including all statistically significant terms, JMP is used. The full model provides insights into whether the underlying assumption of

additive normally distributed. Another test will be conducted to reduce multicollinearity, which could occur because of the correlation among the noise factors. The stepwise regression function in JMP allows adding and removing terms at each step. While doing so, the order of the factors entering the model can be observed. This is helpful to see which ones are more important.

The ratio of the variation explained by the model to the total variation included in the data is called R^2, the coefficient of determination.[34] The model shown in Figure 31 has a high R^2 value of 0.9752.

Response Mean(#HITS)

Summary of Fit

RSquare	0,975171
RSquare Adj	0,97483
Root Mean Square Error	2,862534
Mean of Response	28,54883
Observations (or Sum Wgts)	1625

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	22	515571,99	23435,1	2859,996
Error	1602	13126,95	8,2	Prob > F
C. Total	1624	528698,94		0,0000

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	VIF
Intercept	-4,448744	0,65584	-6,78	<,0001	.
Blockades A	5,8087652	0,06438	90,23	0,0000	2,0857967
Blockades B	4,6175575	0,062567	73,80	0,0000	1,9699865
Blockades C	2,8279617	0,066547	42,50	<,0001	2,2286196
Latency (real)	0,1175132	0,004492	26,16	<,0001	1,0003076
Pause (real)	0,0265991	0,011119	2,39	0,0169	1,0007104
SENSOR GRID Reliability	-0,015095	0,002689	-5,61	<,0001	1,0001897
SENSOR Range	-0,000773	0,000881	-0,88	0,3801	1,0000306
SENSOR GRID Capacity	-0,003143	0,000969	-3,24	0,0012	1,0001391
(Blockades A-2,32)*(Blockades B-2,32)	0,2400935	0,054652	4,39	<,0001	3,3624782
(Blockades A-2,32)*(Blockades C-2,32)	0,1577005	0,05329	2,96	0,0031	3,0786625
(Blockades A-2,32)*(Latency (real)-33,0154)	0,0325866	0,003318	9,82	<,0001	1,3847628
(Blockades A-2,32)*(SENSOR GRID Reliability-55,0154)	-0,004384	0,001688	-2,60	0,0095	1,0000141
(Blockades B-2,32)*(Blockades C-2,32)	-0,467604	0,065035	-7,19	<,0001	4,3276564
(Blockades C-2,32)*(Latency (real)-33,0154)	0,0085581	0,003318	2,58	0,0100	1,3847487
(Latency (real)-33,0154)*(SENSOR GRID Capacity-375,015)	0,0001423	0,000057	2,51	0,0121	1,0390151
(Pause (real)-13,2154)*(SENSOR Range-462,508)	0,0005381	0,000149	3,62	0,0003	1,1091384
(Pause (real)-13,2154)*(SENSOR GRID Capacity-375,015)	-0,000606	0,000201	-3,02	0,0026	1,1401537
(Blockades A-2,32)*(Blockades A-2,32)	-0,443961	0,045012	-9,86	<,0001	2,1648379
(Blockades B-2,32)*(Blockades B-2,32)	0,5242386	0,063046	8,32	<,0001	4,2470694
(Blockades C-2,32)*(Blockades C-2,32)	0,3164313	0,046332	6,83	<,0001	2,2936728
(Latency (real)-33,0154)*(Latency (real)-33,0154)	-0,003095	0,000378	-8,18	<,0001	1,4081417
(SENSOR GRID Reliability-55,0154)*(SENSOR GRID Reliability-55,0154)	0,0003798	0,000131	2,90	0,0037	1,324107

Figure 31. The full regression model.

The fit seems to be good. But a high R^2 value does not automatically guarantee a good model. Over-fitting, having too many factors, reduces the usability for predicting and interpretability. This will be examined in the next section. To reach this high R^2

34 Douglas C. Montgomery, "Introduction to Linear Regression Analysis," 3rd Edition, 2001, p. 39.

level, 22 predictors plus the intercept term are necessary. The model still includes terms which do not influence the outcome significantly. For example, the senor range (Range) has a p-value of 0.38. This would normally exclude the term; but, an interaction term involving the range is significantly important (see connected red boxes). Good regression modeling does not allow taking out main effects that are involved in an interaction.

The JMP software package provides a test on multicollinearity. The Variance Inflation Factor (VIF) is automatically calculated for all regressors. "The VIF for each term in the model measures the combined effect of the dependences among the regressors on the variance of the term."[35] VIF values exceeding 5 or 10 are an indication of multicollinearity. VIF also shows the involved factor. In this case, all VIF are below 5, thanks to our efficient design. Multicollinearity seems to be no issue. The author ran another small calculation to cross check this result. The correlation matrix including only the regressors is used.[36] The determinant of the correlation matrix has the range between 0 and 1. The result for a matrix including at least one pair of linearly dependent regressors is 0. On the other hand orthogonal regressors are indicated by a value of 1 for the determinant. The correlation matrix (see Chapter 3 Figure 18) has a determinant of 0.47. The loss of orthogonality is obvious, but the distance from 0 is large enough to confirm the JMP results.

In the next step, the error term is examined. The differences between the fitted regression and the observed values are called residuals. Their distribution is shown in Figure 32.

35 Douglas C. Montgomery, "Introduction to Linear Regression Analysis," 3rd Edition, 2001, p. 337.

36 Douglas C. Montgomery, "Introduction to Linear Regression Analysis," 3rd Edition, 2001, p. 343.

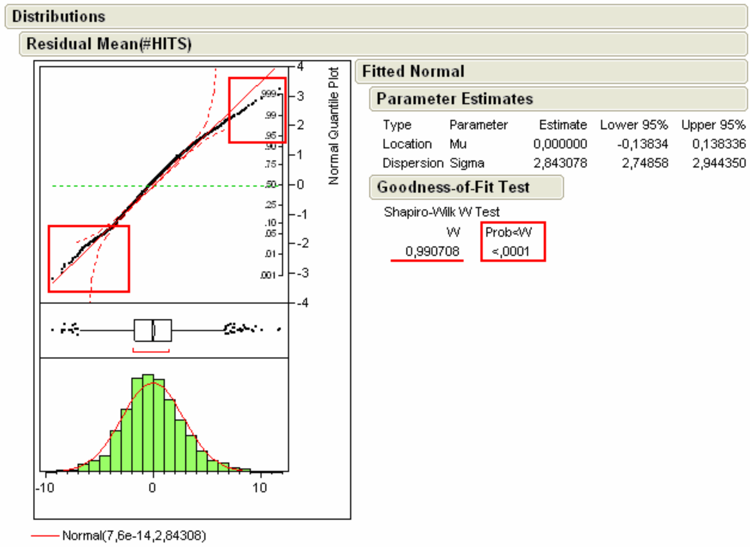


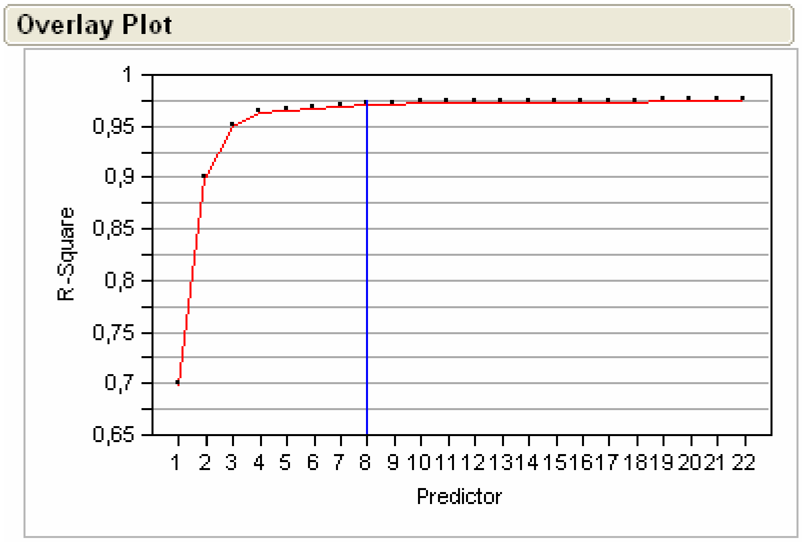
Figure 32. The residual distribution with fitted normal curve and the result of the Shapiro-Wilk W-test.

The residual distribution has a normal bell shape. Looking at the QQ-plot above, the endings show a slightly unusual behavior. Even with a high W value (near 1 means normality), this behavior causes the rejection of the hypothesis that the residuals are normally distributed.

Knowing that a main regression testing assumption is not strictly met, the robustness of regression against slight non-normality is used. The interpretation of the p-values whether a predictor stays in the model or not, has to be done more carefully due to the slightly non-normal behavior of the error terms. However, this does not impact the significant digits of the p-values.

4. Reduced Regression Model

The section deals with the question of how to reduce the number of predictors while still maintaining a good model fit. During the stepwise regression the author noted the improvements in the R^2 value whenever a new predictor was added. The graph in Figure 33 shows the improvement curve as a function of added regressors.



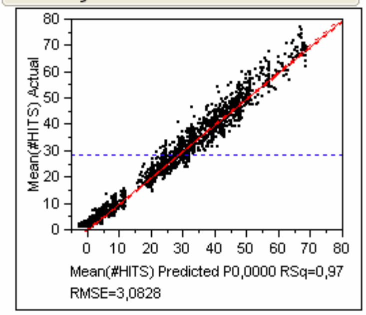
1) Blockades A
2) Blockades B
3) Blockades C
4) Latency (real)
5) Blockades A *Latency (real)
6) Latency (real)*Latency (real)
7) Blockades B*Blockades B
8) Blockades A*Blockades A
9) Blockades C*Blockades C
10) Blockades B*Blockades C
11) Reliability
12) Blockades A*Blockades B
13) Pause (real)
14) Capacity
15) Pause (real)*Capacity
16) Reliability*Reliability
17) Range
18) Pause (real)* Range
19) Latency (real)*Capacity
20) Blockades A*Blockades C
21) Blockades A*Reliability
22) Blockades C*Latency (real)

Figure 33. R^2 improvement by adding a new predictor.

Looking at the chart, it is remarkable that Blockades A, B and C as main effects explain 95% of the variation in the data. This result corresponds to the regression tree in the previous section where the first 13 steps created an R^2 of about 95%. Again, Latency appears as the first communication factor. The next set of terms are the interactions between Blockades A and latency and the quadratic terms of Latency, Blockades B, A and C. With the 8th element an R^2 of 97% is reached. The added improvement by adding more predictors is minimal. Therefore, the author decided to drop the elements appearing after the 8th prdeictor and ignore these terms. The resulting model still explains 97.1% of the variation. The reduced model is shown in Figure 34.

Response Mean(#HITS)

Actual by Predicted Plot



Summary of Fit

RSquare	0,970951
RSquare Adj	0,970807
Root Mean Square Error	3,082834
Mean of Response	28,54883
Observations (or Sum Wgts)	1625

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	8	513340,69	64167,6	6751,737
Error	1616	15358,24	9,5	Prob > F
C. Total	1624	528698,94		0,0000

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-5,654431	0,261101	-21,66	<,0001
Blockades A	5,7354801	0,065913	87,02	0,0000
Blockades B	4,6237153	0,063442	72,88	0,0000
Blockades C	2,9598465	0,064269	46,05	<,0001
Latency (real)	0,1175985	0,004837	24,31	<,0001
(Blockades A-2,32)*(Latency (real)-33,0154)	0,0371252	0,003037	12,23	<,0001
(Blockades A-2,32)*(Blockades A-2,32)	-0,261045	0,03734	-6,99	<,0001
(Blockades B-2,32)*(Blockades B-2,32)	0,3935432	0,035732	11,01	<,0001
(Latency (real)-33,0154)*(Latency (real)-33,0154)	-0,003664	0,000343	-10,67	<,0001

Figure 34. Reduced regression model.

The interaction term (Blockades A*Latency) can be interpreted as both factors driving the number of hits up additionally when they are at high settings jointly, and vice versa. The results show again that latency is the most important controllable factor.

The model reduction eliminates the communication factors reliability, capacity, update frequency, and the sensor range. Their impacts on the outcome are marginal and can be neglected in comparison to latency and the red blockades. The scenario implemented in MANA is a static one. The changes only occur at 3 points in time. In a more realistic scenario modeling more dynamic elements, the appearance of other communication factors in a regression model is possible. The same argument will be used in the next section, where thresholds for the communication factors are developed by using a regression tree.

5. Regression Tree for Communication Factors

This approach identifies thresholds for the communication factors. A regression tree is constructed by partitioning exclusively on these factors (see Figure 35).

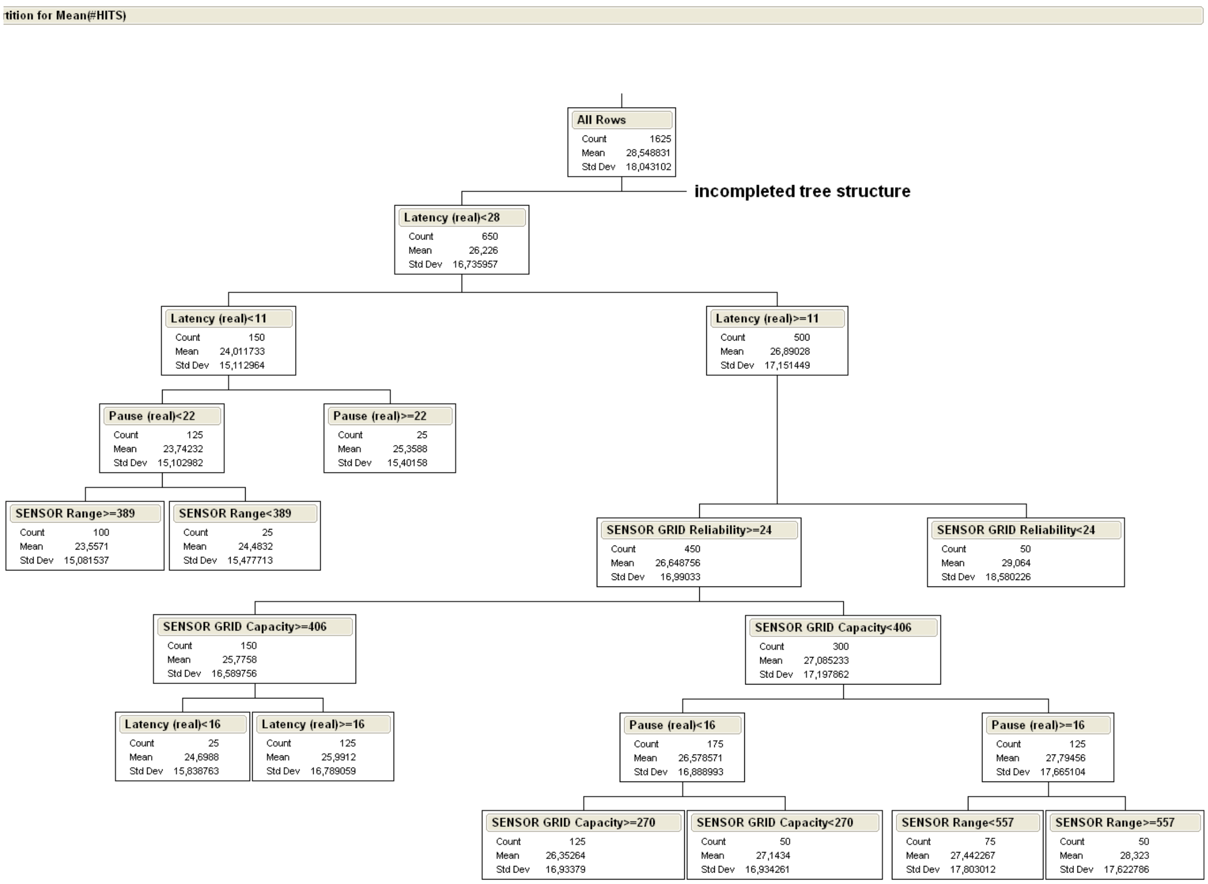


Figure 35. Regression tree for the communication factors. Only the left part of the tree structure is shown.

The discovery tour through the binary tree starts at the root with all 1625 observations. In this case, only the left part with “Latency smaller 28 seconds” is shown for readability. The latency can also be expressed in a length measure which underlines the importance. The convoy runs at 30 km/h through the street channels. In 28 seconds it covers about 225 meters, roughly 8 m/s. Following the left branch, the next latency split occurs at 11 sec, or about 90 meters. When the amount of time between updates is smaller than 22 seconds (185 m) an improvement is noticeable. Sensor range, larger than 389 m, has also a positive influence on the outcome. This chain of thresholds is reasonable. It is noted again that the scenario is static. In a dynamic scenario these thresholds are likely to drop significantly.

Following the branch, “Latency > 11”, it seems that a lack of real-time support can be compensated somewhat by a higher reliability and capacity.

6. Discussion and Conclusions

The static character of the model and the weakness resulting from the verification experiment were stated repeatedly. As such, the findings of this experiment have to be read as trends rather than as specific recommendations.

The analysis shows that the scenario is driven primarily by the enemy behavior. The blue force’s reaction relies heavily on precise and non-delayed information. Besides the noise factors, latency has the largest impact on the outcome. The other communication factors do not have the same importance. But, the model does not allow the conclusion that they are unimportant. The lack of a dynamic threat in the scenario and the MANA limitations make it impossible to strictly exclude these factors.

V. FINAL DISCUSSION AND RECOMMENDATIONS

The previous chapter has revealed that MANA can produce useful insights. But, the author is not totally convinced of their meaningfulness. In particular, the analysis on the model shows that it has limitations. However, it is still statistically stable on average, as observed by the paired t-test. Due to these limitations, the objective of exploring communication aspects cannot be completely and satisfactorily answered. Therefore, the author discusses ideas for further research based on the perspectives gained here. These studies are difficult when it comes to finding solutions to combine a complex terrain and a creative movement algorithm. In this chapter, improvements and alternative approaches are introduced and discussed. First, suggestions for improving the existing model that the author could not implement due to time constraints are discussed. Then, a short general excursion is made into network analysis in order to show another potential decision making tool. The last discussion point includes a totally different approach. Instead of using a time step agent-based model, the potential of a discrete event simulation is explained.

A. IMPROVEMENTS WITHIN THE EXISTING MODEL

The replication of runs uncovered that MANA's movement algorithm and an urban terrain are a challenging combination. The author chose to let the convoy use the whole width of the streets. This led to a situation where the convoy often got stuck and chose to look for cover against enemy fire rather than escape. As a result, the MOEs were affected negatively. There are two ways to overcome this bad situation. One solution is to increase the convoy's desire to stay away from walls at a specified distance. This could keep the convoy in the middle of the road. The alternative, preferred by the author, would be to restrict the convoy moves to a line. Imagine a railroad track, one narrow guiding line in the middle of the street that allows the convoy's movements. The street width has to be kept large to allow exposure to hostile fire. Of course, the desire settings have to be adjusted. The repelling character of blockade or 'logic helpers' would

be increased. With these changes, the convoy has no chance to circumvent a logic helper and can not ignore its warning signal.

B. ALTERNATIVE DECISION TOOL

The MANA agents move because of their desires. They want to go towards a goal or stay away from enemies. A penalty function delivers the movement direction by taking the minimum penalty associated with each possible choice. All of these decisions are made locally at each time step. A projection into future steps is not implemented, which is contrary to real world decision making.

The modeled scenario is a classic routing problem within a network context. The network consists of nodes and arcs. The nodes are crossroads and the arcs are connecting streets between two nodes. A blockade is realized as a high arc cost. Network analysis provides several algorithms[37] to find the best path through such a network. In this case, the algorithm would deliver the safest way—given the information available. The algorithm results in an ordered list of nodes the convoy has to visit. The nodes can be interpreted as waypoints which attract the convoy. Only the next waypoint can be seen by the convoy. Every time a new blockade shows up, the associated arc cost is increased and the list recalculated. Therefore, movements like turning around and going back to a waypoint already visited can be implemented.

The underlying network structure should be implemented as a third map in MANA. The convoy's decision would be made globally, which is more realistic in an urban environment when non-local information is available. This map completes the situational awareness. IT-SimBw, the simulation software developed in Germany, includes a network map. Preliminary results reported by the creators look promising.

37 Ravindra K. Ahuja, Thomas L. Magnanti, and James B. Orlin, "Network Flows: Theory, Algorithm, and Applications," 1993.

C. DISCRETE EVENT SIMULATION

The simulation community has a divided opinion on time step models, like MANA. Some analysts totally deny the usefulness of time step models and prefer a discrete event simulation (DES).[38] MANA is a time step model, even though events occur and the agents change their states. The author will briefly outline how a DES model could look like.

Picking up the network idea from the previous section, the street map can be implemented as a graph with nodes and arcs. The blockades are associated as cost on the arcs. The extra cost can be seen as additional exposure to hostile fire and be expressed as the number of hits. Each node knows which incoming/outgoing arc is a blocked street and how many hits a convoy could suffer passing this node. The convoy itself carries lists containing the network information, that is, whether the streets are useable, unknown or blocked. One list provides the estimated number of hits the convoy would suffer when passing the node given its known blockade setting. Another list provides the estimated time it would take to traverse an arc. These databases are regularly updated due to changes in the convoy's situational awareness. The visited nodes are stored in a stack. The blockades and their appearance time can be totally randomized, contrary to the scripting of MANA. In some sense, blockade setting can be modeled as a smarter way of trying to set up ambushes.

The communication link between a sensor and the convoy can be modeled. For example, latency could be achieved by entering an additional delay before the lists carried by the convoy are updated. The reliability could be implemented by the decision of whether the convoy's lists are renewed or not. An update frequency is modeled by periodically scheduling the next sensor updates.

In an event driven simulation, the convoy makes a global decision, using a shortest path algorithm, regarding which route to take. The arrival at the next node is scheduled depending on the arc length (traveling time). The algorithm tries to minimize

38 Wikipedia.org (November 2006), Definition: "In discrete event simulation, the operation of a system is represented as a chronological sequence of events. Each event occurs at an instant in time and marks a change of state in the system."

the number of hits while getting to the goal in a reasonable time. The convoy listens to the sensor. Every time its graph is updated a new path decision is made—perhaps after some delay. In the case where the convoy returns to a prior node an additional delay is activated, perhaps resulting in a longer exposure to fire. On its way through the streets the convoy collects the number of hits stored at the nodes, or incurs extra costs by fighting through a blockade.

In retrospect, a discrete event simulation on an arc-node structure seems to be most appropriate approach to gain insights about communication aspects of convoys in urban terrain.

APPENDIX

This Appendix contains tables and figures that complete the experimental design and the following analysis. The complete data table for the noise factors combining a NOLH design and 8 additional design points is presented. For the analysis part, the Ruby code is inserted. In the main text, only one design point was explicitly examined in order to assess the model's quality. The complete analysis on all design points is summarized in this Appendix.

	Super_agent 1	Super_agent 2	Super_agent 3	Blockade A	Blockade B	Blockade C	Blockade total
Low Level	**7**	**10**	**13**				
High Level	**11**	**14**	**17**				
Decimals	**0**	**0**	**0**				
DP_1	8	14	16	4	1	2	7
DP_2	7	11	17	5	4	1	10
DP_3	8	12	13	4	3	5	12
DP_4	8	13	14	4	2	4	10
DP_5	10	14	15	2	1	3	6
DP_6	11	11	15	1	4	3	8
DP_7	10	11	17	2	4	1	7
DP_8	9	14	16	3	1	2	6
DP_9	9	12	15	3	3	3	9
DP_10	10	10	14	2	5	4	11
DP_11	11	13	14	1	2	4	7
DP_12	11	12	17	1	3	1	5
DP_13	12	12	16	0	3	2	5
DP_14	8	10	15	4	5	3	12
DP_15	7	13	16	5	2	2	9
DP_16	9	13	13	3	2	5	10
DP_17	9	11	14	3	4	4	11
DP_18	11	15	18	1	0	0	1
DP_19	12	14	18	0	1	0	1
DP_20	12	15	17	0	0	1	1
DP_21	11	14	18	1	1	0	2
DP_22	11	15	17	1	0	1	2
DP_23	12	14	17	0	1	1	2
DP_24	11	14	17	1	1	1	3
DP_25	7	10	13	5	5	5	15

Table 4. (Appendix) Complete spreadsheet for the noise factors. Design points (DP) 1 to 17 are the NOLH design points. 18 to 25 are additional ones. In the model the super-agents are varied. The resulting blockade settings are calculated in the right part.

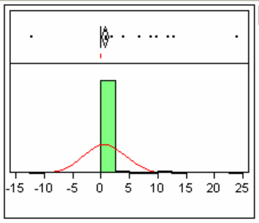
```
run = 0
outputFile =File.new("c:/thesis/sep27/HitsMissingDP27sep.txt","w")
outputFile<<"RUN,EXCURSION,#HITS\n"
while run < 1
  excursion = 0
  while excursion < 100
   filename = "agt_end."+run.to_s+"."+excursion.to_s+".csv"
   path = "c:/thesis/sep27/missingdp/"+filename
   readFile = File.open(path,"r")
   count = 0
   while count < 7
    line = readFile.gets
    values = line.chomp.split(/,/)
    count = count + 1
   end
   hits = values[10]
   xpos=values[4]
   ypos=values[5]

outputFile<<run.to_s+","+excursion.to_s+","+hits.to_s+","+xpos.to_s+"-
"+ypos.to_s+"\n"
   excursion = excursion + 1
  end
```

Figure 36. (Appendix) Ruby-code used for extracting the important data element out of the provide agent-end data file. MANA writes ordered output files. These files can be simply accessed, as the variable *filename* demonstrates.

Blockade A=0, Blockade B=0, Blockade C=1

Distributions

Hit Difference



Quantiles

100.0%	maximum	24,00
99.5%		24,00
97.5%		12,47
90.0%		1,00
75.0%	quartile	0,00
50.0%	median	0,00
25.0%	quartile	0,00
10.0%		0,00
2.5%		0,00
0.5%		-12,00
0.0%	minimum	-12,00

Moments

Mean	0,76
Std Dev	3,5451489
Std Err Mean	0,3545149
upper 95% Mean	1,4634345
lower 95% Mean	0,0565655
N	100

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	0,760000	0,056566	1,463434
Dispersion	Sigma	3,545149	3,112665	4,118312

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0,362865	0,0000

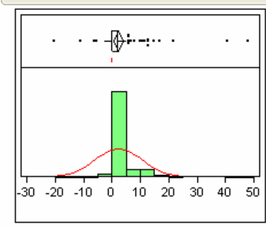
Test Mean=value

Hypothesized Value	0
Actual Estimate	0,76
df	99
Std Dev	3,54515
	t Test
Test Statistic	2,1438
Prob > |t|	0,0345
Prob > t	0,0173
Prob < t	0,9827

Blockade A=0, Blockade B=1, Blockade C=0

Distributions

Hit Difference



Quantiles

100.0%	maximum	48,00
99.5%		48,00
97.5%		31,02
90.0%		11,90
75.0%	quartile	2,00
50.0%	median	0,00
25.0%	quartile	0,00
10.0%		0,00
2.5%		-8,37
0.5%		-20,00
0.0%	minimum	-20,00

Moments

Mean	2,49
Std Dev	8,0069351
Std Err Mean	0,8006935
upper 95% Mean	4,0787496
lower 95% Mean	0,9012504
N	100

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	2,490000	0,901250	4,078750
Dispersion	Sigma	8,006935	7,030144	9,301458

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0,578002	<,0001

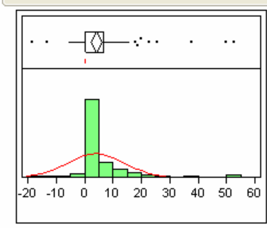
Test Mean=value

Hypothesized Value	0
Actual Estimate	2,49
df	99
Std Dev	8,00694
	t Test
Test Statistic	3,1098
Prob > |t|	0,0024
Prob > t	0,0012
Prob < t	0,9988

Blockade A=0, Blockade B=1, Blockade C=1

Distributions

Hit Difference



Quantiles

100.0%	maximum	53,00
99.5%		53,00
97.5%		43,70
90.0%		15,70
75.0%	quartile	6,75
50.0%	median	0,00
25.0%	quartile	0,00
10.0%		0,00
2.5%		-9,32
0.5%		-18,00
0.0%	minimum	-18,00

Moments

Mean	4,15
Std Dev	10,054774
Std Err Mean	1,0054774
upper 95% Mean	6,1450853
lower 95% Mean	2,1549147
N	100

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	4,15000	2,154915	6,14509
Dispersion	Sigma	10,05477	8,828161	11,68038

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0,666070	<,0001

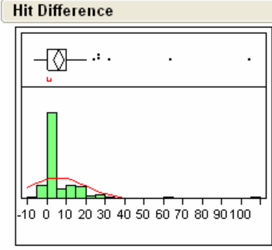
Test Mean=value

Hypothesized Value	0
Actual Estimate	4,15
df	99
Std Dev	10,0548
	t Test
Test Statistic	4,1274
Prob > |t|	<,0001
Prob > t	<,0001
Prob < t	1,0000

Blockade A=1, Blockade B=0, Blockade C=0

Distributions

Hit Difference



Quantiles

100.0%	maximum	105,0
99.5%		105,0
97.5%		47,7
90.0%		18,0
75.0%	quartile	9,8
50.0%	median	0,0
25.0%	quartile	0,0
10.0%		-0,9
2.5%		-3,0
0.5%		-7,0
0.0%	minimum	-7,0

Moments

Mean	6,16
Std Dev	13,969462
Std Err Mean	1,3969462
upper 95% Mean	8,9318443
lower 95% Mean	3,3881557
N	100

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	6,16000	3,38816	8,93184
Dispersion	Sigma	13,96946	12,26528	16,22798

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0,539052	<,0001

Test Mean=value

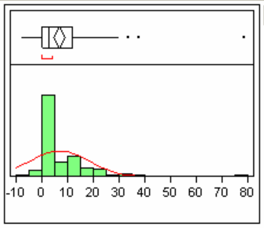
Hypothesized Value	0
Actual Estimate	6,16
df	99
Std Dev	13,9695
	t Test
Test Statistic	4,4096
Prob > |t|	<,0001
Prob > t	<,0001
Prob < t	1,0000

Figure 37. (Appendix) The sequence of statistical tests conducted to assess the model quality. Due to readability the 25 design points are split.

Blockade A=1, Blockade B=0, Blockade C=1

Distributions

Hit Difference



Normal(6,82,11,4136)

Quantiles

100.0%	maximum	79,00
99.5%		79,00
97.5%		35,90
90.0%		20,80
75.0%	quartile	12,00
50.0%	median	2,50
25.0%	quartile	0,00
10.0%		0,00
2.5%		-3,47
0.5%		-8,00
0.0%	minimum	-8,00

Moments

Mean	6,82
Std Dev	11,413602
Std Err Mean	1,1413602
upper 95% Mean	9,0847062
lower 95% Mean	4,5552938
N	100

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	6,82000	4,55529	9,08471
Dispersion	Sigma	11,41360	10,02122	13,25890

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0,694505	<,0001

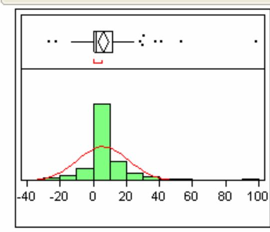
Test Mean=value

Hypothesized Value	0
Actual Estimate	6,82
df	99
Std Dev	11,4136
	t Test
Test Statistic	5,9753
Prob > |t|	<,0001
Prob > t	<,0001
Prob < t	1,0000

Blockade A=1, Blockade B=1, Blockade C=0

Distributions

Hit Difference



Normal(6,11,15,3655)

Quantiles

100.0%	maximum	99,00
99.5%		99,00
97.5%		47,70
90.0%		21,80
75.0%	quartile	11,50
50.0%	median	1,50
25.0%	quartile	0,00
10.0%		-5,90
2.5%		-17,80
0.5%		-26,00
0.0%	minimum	-26,00

Moments

Mean	6,11
Std Dev	15,36551
Std Err Mean	1,536551
upper 95% Mean	9,1588505
lower 95% Mean	3,0611495
N	100

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	6,11000	3,06115	9,15885
Dispersion	Sigma	15,36551	13,49102	17,84973

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0,762453	<,0001

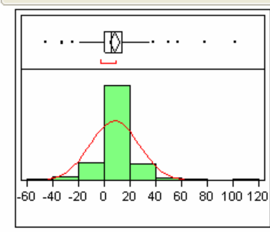
Test Mean=value

Hypothesized Value	0
Actual Estimate	6,11
df	99
Std Dev	15,3655
	t Test
Test Statistic	3,9764
Prob > |t|	0,0001
Prob > t	<,0001
Prob < t	0,9999

Blockade A=1, Blockade B=1, Blockade C=1

Distributions

Hit Difference



Normal(8,29,18,9728)

Quantiles

100.0%	maximum	102,0
99.5%		102,0
97.5%		68,0
90.0%		25,7
75.0%	quartile	14,0
50.0%	median	5,0
25.0%	quartile	0,0
10.0%		-5,0
2.5%		-32,0
0.5%		-45,0
0.0%	minimum	-45,0

Moments

Mean	8,29
Std Dev	18,972758
Std Err Mean	1,8972758
upper 95% Mean	12,054607
lower 95% Mean	4,5253931
N	100

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	8,29000	4,52539	12,05461
Dispersion	Sigma	18,97276	16,65821	22,04018

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0,833173	<,0001

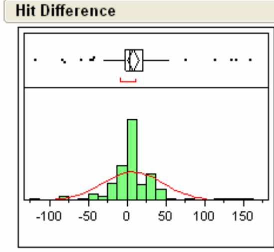
Test Mean=value

Hypothesized Value	0
Actual Estimate	8,29
df	99
Std Dev	18,9728
	t Test
Test Statistic	4,3694
Prob > |t|	<,0001
Prob > t	<,0001
Prob < t	1,0000

Blockade A=1, Blockade B=2, Blockade C=4

Distributions

Hit Difference



Normal(8,39,38,4358)

Quantiles

100.0%	maximum	161,0
99.5%		161,0
97.5%		139,8
90.0%		43,4
75.0%	quartile	21,0
50.0%	median	4,0
25.0%	quartile	-3,0
10.0%		-24,0
2.5%		-80,4
0.5%		-116,0
0.0%	minimum	-116,0

Moments

Mean	8,39
Std Dev	38,435804
Std Err Mean	3,8435804
upper 95% Mean	16,016497
lower 95% Mean	0,7635027
N	100

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	8,39000	0,76350	16,01650
Dispersion	Sigma	38,43580	33,74690	44,64992

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0,842549	<,0001

Test Mean=value

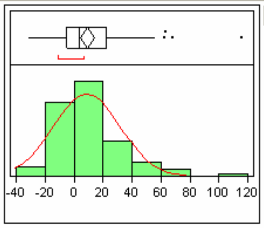
Hypothesized Value	0
Actual Estimate	8,39
df	99
Std Dev	38,4358
	t Test
Test Statistic	2,1829
Prob > |t|	0,0314
Prob > t	0,0157
Prob < t	0,9843

Figure 38. (Appendix) The sequence of statistical tests conducted to assess the model quality. Due to readability the 25 design points are split.

Blockade A=1, Blockade B=3, Blockade C=1

Distributions

Hit Difference



Normal(9,14,23,18)

Quantiles

100.0%	maximum	116,0
99.5%		116,0
97.5%		66,4
90.0%		39,6
75.0%	quartile	22,0
50.0%	median	4,0
25.0%	quartile	-5,0
10.0%		-12,8
2.5%		-29,5
0.5%		-32,0
0.0%	minimum	-32,0

Moments

Mean	9,14
Std Dev	23,180024
Std Err Mean	2,3180024
upper 95% Mean	13,73942
lower 95% Mean	4,5405802
N	100

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	9,14000	4,54058	13,73942
Dispersion	Sigma	23,18002	20,35222	26,92766

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0,894650	<,0001

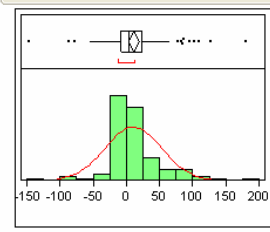
Test Mean=value

Hypothesized Value	0
Actual Estimate	9,14
df	99
Std Dev	23,18
	t Test
Test Statistic	3,9431
Prob > |t|	0,0002
Prob > t	<,0001
Prob < t	0,9999

Blockade A=1, Blockade B=4, Blockade C=3

Distributions

Hit Difference



Normal(11,37,42,534)

Quantiles

100.0%	maximum	181,0
99.5%		181,0
97.5%		119,1
90.0%		65,7
75.0%	quartile	24,0
50.0%	median	4,0
25.0%	quartile	-8,8
10.0%		-19,9
2.5%		-80,3
0.5%		-146,0
0.0%	minimum	-146,0

Moments

Mean	11,37
Std Dev	42,53404
Std Err Mean	4,253404
upper 95% Mean	19,809676
lower 95% Mean	2,9303237
N	100

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	11,37000	2,93032	19,80968
Dispersion	Sigma	42,53404	37,34518	49,41074

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0,887186	<,0001

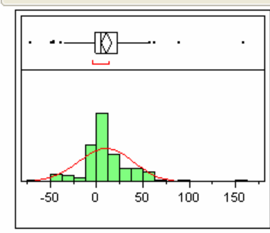
Test Mean=value

Hypothesized Value	0
Actual Estimate	11,37
df	99
Std Dev	42,534
	t Test
Test Statistic	2,6732
Prob > |t|	0,0088
Prob > t	0,0044
Prob < t	0,9956

Blockade A=2, Blockade B=1, Blockade C=3

Distributions

Hit Difference



Normal(10,36,29,201)

Quantiles

100.0%	maximum	159,0
99.5%		159,0
97.5%		75,8
90.0%		43,0
75.0%	quartile	22,0
50.0%	median	5,0
25.0%	quartile	-1,8
10.0%		-16,5
2.5%		-46,4
0.5%		-70,0
0.0%	minimum	-70,0

Moments

Mean	10,36
Std Dev	29,200982
Std Err Mean	2,9200982
upper 95% Mean	16,154108
lower 95% Mean	4,5658916
N	100

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	10,36000	4,56589	16,15411
Dispersion	Sigma	29,20098	25,63866	33,92206

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0,883189	<,0001

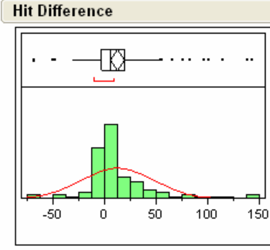
Test Mean=value

Hypothesized Value	0
Actual Estimate	10,36
df	99
Std Dev	29,201
	t Test
Test Statistic	3,5478
Prob > |t|	0,0006
Prob > t	0,0003
Prob < t	0,9997

Blockade A=2, Blockade B=3, Blockade C=2

Distributions

Hit Difference



Normal(12,97,34,6991)

Quantiles

100.0%	maximum	144,0
99.5%		144,0
97.5%		126,4
90.0%		54,8
75.0%	quartile	19,5
50.0%	median	5,5
25.0%	quartile	-3,8
10.0%		-10,9
2.5%		-58,5
0.5%		-68,0
0.0%	minimum	-68,0

Moments

Mean	12,97
Std Dev	34,699127
Std Err Mean	3,4699127
upper 95% Mean	19,85506
lower 95% Mean	6,0849405
N	100

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	12,97000	6,08494	19,85506
Dispersion	Sigma	34,69913	30,46607	40,30912

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0,840938	<,0001

Test Mean=value

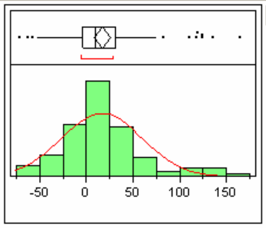
Hypothesized Value	0
Actual Estimate	12,97
df	99
Std Dev	34,6991
	t Test
Test Statistic	3,7378
Prob > |t|	0,0003
Prob > t	0,0002
Prob < t	0,9998

Figure 39. (Appendix) The sequence of statistical tests conducted to assess the model quality. Due to readability the 25 design points are split.

Blockade A=2, Blockade B=4, Blockade C=1

Distributions

Hit Difference



Quantiles

100.0%	maximum	165,0
99.5%		165,0
97.5%		130,2
90.0%		71,7
75.0%	quartile	31,0
50.0%	median	10,0
25.0%	quartile	-3,8
10.0%		-35,8
2.5%		-59,4
0.5%		-71,0
0.0%	minimum	-71,0

Moments

Mean	17,32
Std Dev	43,209352
Std Err Mean	4,3209352
upper 95% Mean	25,893673
lower 95% Mean	8,7463272
N	100

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	17,32000	8,74633	25,89367
Dispersion	Sigma	43,20935	37,93811	50,19523

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0,928616	<,0001

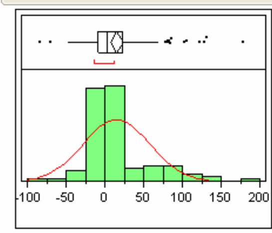
Test Mean=value

Hypothesized Value	0
Actual Estimate	17,32
df	99
Std Dev	43,2094
	t Test
Test Statistic	4,0084
Prob > |t|	0,0001
Prob > t	<,0001
Prob < t	0,9999

Blockade A=2, Blockade B=5, Blockade C=4

Distributions

Hit Difference



Quantiles

100.0%	maximum	180,0
99.5%		180,0
97.5%		130,9
90.0%		83,0
75.0%	quartile	22,8
50.0%	median	3,5
25.0%	quartile	-9,0
10.0%		-16,9
2.5%		-58,5
0.5%		-82,0
0.0%	minimum	-82,0

Moments

Mean	15,79
Std Dev	42,926833
Std Err Mean	4,2926833
upper 95% Mean	24,307615
lower 95% Mean	7,2723849
N	100

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	15,79000	7,27238	24,30762
Dispersion	Sigma	42,92683	37,69005	49,86704

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0,874512	<,0001

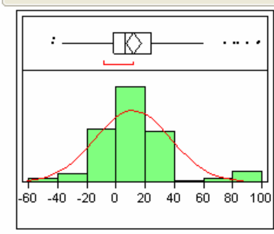
Test Mean=value

Hypothesized Value	0
Actual Estimate	15,79
df	99
Std Dev	42,9268
	t Test
Test Statistic	3,6784
Prob > |t|	0,0004
Prob > t	0,0002
Prob < t	0,9998

Blockade A=3, Blockade B=1, Blockade C=2

Distributions

Hit Difference



Quantiles

100.0%	maximum	99,00
99.5%		99,00
97.5%		94,32
90.0%		33,90
75.0%	quartile	23,75
50.0%	median	6,50
25.0%	quartile	-1,75
10.0%		-9,80
2.5%		-39,38
0.5%		-43,00
0.0%	minimum	-43,00

Moments

Mean	12,11
Std Dev	25,961469
Std Err Mean	2,5961469
upper 95% Mean	17,261319
lower 95% Mean	6,9586813
N	100

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	12,11000	6,95868	17,26132
Dispersion	Sigma	25,96147	22,79435	30,15880

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0,878005	<,0001

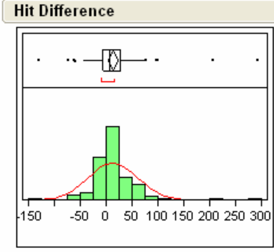
Test Mean=value

Hypothesized Value	0
Actual Estimate	12,11
df	99
Std Dev	25,9615
	t Test
Test Statistic	4,6646
Prob > |t|	<,0001
Prob > t	<,0001
Prob < t	1,0000

Blockade A=3, Blockade B=2, Blockade C=5

Distributions

Hit Difference



Quantiles

100.0%	maximum	294,0
99.5%		294,0
97.5%		151,3
90.0%		62,4
75.0%	quartile	26,8
50.0%	median	6,0
25.0%	quartile	-5,8
10.0%		-21,9
2.5%		-66,2
0.5%		-129,0
0.0%	minimum	-129,0

Moments

Mean	13,81
Std Dev	48,193988
Std Err Mean	4,8193988
upper 95% Mean	23,372733
lower 95% Mean	4,2472672
N	100

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	13,81000	4,24727	23,37273
Dispersion	Sigma	48,19399	42,31465	55,98576

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0,774056	<,0001

Test Mean=value

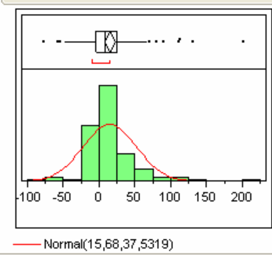
Hypothesized Value	0
Actual Estimate	13,81
df	99
Std Dev	48,194
	t Test
Test Statistic	2,8655
Prob > |t|	0,0051
Prob > t	0,0025
Prob < t	0,9975

Figure 40. (Appendix) The sequence of statistical tests conducted to assess the model quality. Due to readability the 25 design points are split.

Blockade A=3, Blockade B=3, Blockade C=3

Distributions

Hit Difference



Quantiles

100.0%	maximum	203,0
99.5%		203,0
97.5%		123,5
90.0%		59,7
75.0%	quartile	25,3
50.0%	median	8,0
25.0%	quartile	-4,8
10.0%		-14,6
2.5%		-55,0
0.5%		-76,0
0.0%	minimum	-76,0

Moments

Mean	15,68
Std Dev	37,531907
Std Err Mean	3,7531907
upper 95% Mean	23,127145
lower 95% Mean	8,2328554
N	100

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	15,68000	8,23286	23,12714
Dispersion	Sigma	37,53191	32,95327	43,59989

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0,837833	<,0001

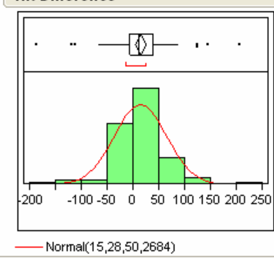
Test Mean=value

Hypothesized Value	0
Actual Estimate	15,68
df	99
Std Dev	37,5319
	t Test
Test Statistic	4,1778
Prob > |t|	<,0001
Prob > t	<,0001
Prob < t	1,0000

Blockade A=3, Blockade B=4, Blockade C=4

Distributions

Hit Difference



Quantiles

100.0%	maximum	208,0
99.5%		208,0
97.5%		136,0
90.0%		71,7
75.0%	quartile	37,5
50.0%	median	11,5
25.0%	quartile	-6,0
10.0%		-28,0
2.5%		-113,8
0.5%		-185,0
0.0%	minimum	-185,0

Moments

Mean	15,28
Std Dev	50,268387
Std Err Mean	5,0268387
upper 95% Mean	25,254339
lower 95% Mean	5,3056615
N	100

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	15,28000	5,30566	25,25434
Dispersion	Sigma	50,26839	44,13599	58,39554

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0,916378	<,0001

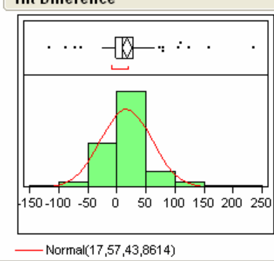
Test Mean=value

Hypothesized Value	0
Actual Estimate	15,28
df	99
Std Dev	50,2684
	t Test
Test Statistic	3,0397
Prob > |t|	0,0030
Prob > t	0,0015
Prob < t	0,9985

Blockade A=4, Blockade B=1, Blockade C=2

Distributions

Hit Difference



Quantiles

100.0%	maximum	236,0
99.5%		236,0
97.5%		142,1
90.0%		65,9
75.0%	quartile	27,8
50.0%	median	10,5
25.0%	quartile	-3,0
10.0%		-15,0
2.5%		-78,1
0.5%		-114,0
0.0%	minimum	-114,0

Moments

Mean	17,57
Std Dev	43,861411
Std Err Mean	4,3861411
upper 95% Mean	26,273055
lower 95% Mean	8,8669446
N	100

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	17,57000	8,86694	26,27306
Dispersion	Sigma	43,86141	38,51062	50,95272

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0,840787	<,0001

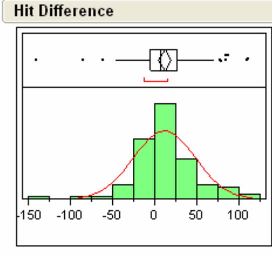
Test Mean=value

Hypothesized Value	0
Actual Estimate	17,57
df	99
Std Dev	43,8614
	t Test
Test Statistic	4,0058
Prob > |t|	0,0001
Prob > t	<,0001
Prob < t	0,9999

Blockade A=4, Blockade B=2, Blockade C=4

Distributions

Hit Difference



Quantiles

100.0%	maximum	112,0
99.5%		112,0
97.5%		98,4
90.0%		58,9
75.0%	quartile	26,8
50.0%	median	7,0
25.0%	quartile	-5,8
10.0%		-23,6
2.5%		-71,4
0.5%		-139,0
0.0%	minimum	-139,0

Moments

Mean	11,93
Std Dev	36,830284
Std Err Mean	3,6830284
upper 95% Mean	19,237927
lower 95% Mean	4,6220727
N	100

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	11,93000	4,62207	19,23793
Dispersion	Sigma	36,83028	32,33724	42,78483

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0,934972	<,0001

Test Mean=value

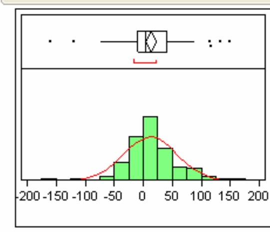
Hypothesized Value	0
Actual Estimate	11,93
df	99
Std Dev	36,8303
	t Test
Test Statistic	3,2392
Prob > |t|	0,0016
Prob > t	0,0008
Prob < t	0,9992

Figure 41. (Appendix) The sequence of statistical tests conducted to assess the model quality. Due to readability the 25 design points are split.

Blockade A=4, Blockade B=3, Blockade C=5

Distributions

Hit Difference



Normal(13,29,45,3862)

Quantiles

100.0%	maximum	150,0
99.5%		150,0
97.5%		126,1
90.0%		74,6
75.0%	quartile	39,5
50.0%	median	5,0
25.0%	quartile	-10,0
10.0%		-32,5
2.5%		-95,9
0.5%		-159,0
0.0%	minimum	-159,0

Moments

Mean	13,29
Std Dev	45,386176
Std Err Mean	4,5386176
upper 95% Mean	22,295602
lower 95% Mean	4,2843981
N	100

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	13,29000	4,28440	22,29560
Dispersion	Sigma	45,38618	39,84937	52,72400

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0,939138	0,0002

Test Mean=value

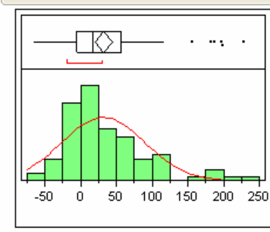
Hypothesized Value	0
Actual Estimate	13,29
df	99
Std Dev	45,3862

	t Test
Test Statistic	2,9282
Prob > |t|	0,0042
Prob > t	0,0021
Prob < t	0,9979

Blockade A=4, Blockade B=5, Blockade C=3

Distributions

Hit Difference



Normal(32,51,58,0965)

Quantiles

100.0%	maximum	230,0
99.5%		230,0
97.5%		198,9
90.0%		113,8
75.0%	quartile	57,0
50.0%	median	17,0
25.0%	quartile	-5,8
10.0%		-24,9
2.5%		-50,8
0.5%		-67,0
0.0%	minimum	-67,0

Moments

Mean	32,51
Std Dev	58,096488
Std Err Mean	5,8096488
upper 95% Mean	44,037604
lower 95% Mean	20,982396
N	100

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	32,51000	20,98240	44,03760
Dispersion	Sigma	58,09649	51,00911	67,48925

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0,902161	<,0001

Test Mean=value

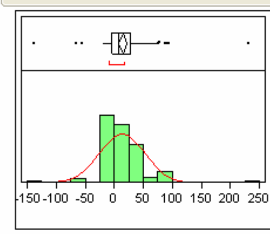
Hypothesized Value	0
Actual Estimate	32,51
df	99
Std Dev	58,0965

	t Test
Test Statistic	5,5959
Prob > |t|	<,0001
Prob > t	<,0001
Prob < t	1,0000

Blockade A=5, Blockade B=2, Blockade C=2

Distributions

Hit Difference



Normal(14,83,38,4274)

Quantiles

100.0%	maximum	232,0
99.5%		232,0
97.5%		93,4
90.0%		50,8
75.0%	quartile	28,8
50.0%	median	7,5
25.0%	quartile	-4,0
10.0%		-11,8
2.5%		-59,2
0.5%		-136,0
0.0%	minimum	-136,0

Moments

Mean	14,83
Std Dev	38,427435
Std Err Mean	3,8427435
upper 95% Mean	22,454837
lower 95% Mean	7,2051632
N	100

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	14,83000	7,20516	22,45484
Dispersion	Sigma	38,42744	33,73955	44,64020

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0,805772	<,0001

Test Mean=value

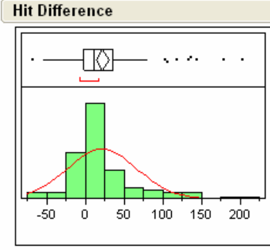
Hypothesized Value	0
Actual Estimate	14,83
df	99
Std Dev	38,4274

	t Test
Test Statistic	3,8592
Prob > |t|	0,0002
Prob > t	0,0001
Prob < t	0,9999

Blockade A=5, Blockade B=4, Blockade C=1

Distributions

Hit Difference



Normal(22,56,44,9532)

Quantiles

100.0%	maximum	205,0
99.5%		205,0
97.5%		162,1
90.0%		77,9
75.0%	quartile	35,0
50.0%	median	12,0
25.0%	quartile	-2,0
10.0%		-9,0
2.5%		-52,9
0.5%		-66,0
0.0%	minimum	-66,0

Moments

Mean	22,56
Std Dev	44,953246
Std Err Mean	4,4953246
upper 95% Mean	31,479699
lower 95% Mean	13,640301
N	100

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	22,56000	13,64030	31,47970
Dispersion	Sigma	44,95325	39,46926	52,22107

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0,835160	<,0001

Test Mean=value

Hypothesized Value	0
Actual Estimate	22,56
df	99
Std Dev	44,9532

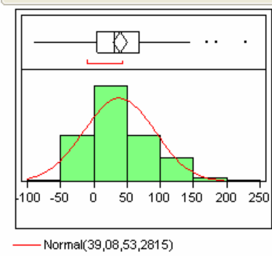
	t Test
Test Statistic	5,0185
Prob > |t|	<,0001
Prob > t	<,0001
Prob < t	1,0000

Figure 42. (Appendix) The sequence of statistical tests conducted to assess the model quality. Due to readability the 25 design points are split.

Blockade A=5, Blockade B=5, Blockade C=5

Distributions

Hit Difference



Quantiles

100.0%	maximum	230,0
99.5%		230,0
97.5%		177,6
90.0%		108,0
75.0%	quartile	68,8
50.0%	median	31,5
25.0%	quartile	4,3
10.0%		-20,7
2.5%		-44,9
0.5%		-92,0
0.0%	minimum	-92,0

Moments

Mean	39,08
Std Dev	53,281543
Std Err Mean	5,3281543
upper 95% Mean	49,652214
lower 95% Mean	28,507786
N	100

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	39,08000	28,50779	49,65221
Dispersion	Sigma	53,28154	46,78156	61,89585

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0,958710	0,0033

Test Mean=value

Hypothesized Value	0
Actual Estimate	39,08
df	99
Std Dev	53,2815

	t Test
Test Statistic	7,3346
Prob > |t|	<,0001
Prob > t	<,0001
Prob < t	1,0000

Figure 43. (Appendix) The sequence of statistical tests conducted to assess the model quality. Due to readability the 25 design points are split.

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